

AN ASSESSMENT OF GROUNDWATER FLOW MECHANISMS FROM THE FOUNTAIN EAST AND WEST KARST COMPARTMENTS IN PRETORIA, SOUTH AFRICA

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Submitted in fulfilment of the requirements for the degree

Magister Scientiae in Geohydrology

in the

Faculty of Natural and Agricultural Sciences
(Institute for Groundwater Studies)

at the

University of the Free State

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February 2024



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DECLARATION

I, Katlego France Maake, hereby declare that the dissertation hereby submitted by me to the Institute for Groundwater Studies in the Faculty of Natural and Agricultural Sciences at the University of the Free State, in fulfilment of the degree of Magister Scientiae, is my own independent work. It has not previously been submitted by me to any other institution of higher education. In addition, I declare that all sources cited have been acknowledged by means of a list of references.

I furthermore cede copyright of the dissertation and its contents in favour of the University of the Free State.

A handwritten signature in black ink, appearing to read 'Katlego Maake', with a stylized, cursive script.

Katlego Maake

February 2024

ACKNOWLEDGEMENTS

I would hereby like to express my sincere gratitude to all who have motivated and helped me in the completion of this thesis:

- Dr Amy Allwright for believing in me and providing me with guidance during the concept stage of this project until completion.
- Dumisani Tshabalala from the City of Tshwane's Rietvlei Water Treatment Plant, for providing me with the spring discharge data for 2016 to 2021 monitoring events.
- My wife, Dimakatso for the support and encouragement.
- My lovely daughter, Lesedi, for giving me all inspiration needed to complete this project.
- My late mother for believing in me during tough times, may her soul rest in peace.
- Lastly, my colleagues at Environmental Resources Management for the support shown while completing this project.

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LIST OF ABBREVIATIONS AND ACRONYMS

MI	Million Litres
DWS	Department of Water and Sanitation
CoT	City of Tshwane
DK	Degree of Karstification
FEWKA	Fountain East and West Karst Aquifer
GDE	Groundwater Dependent Ecosystem
UN	United Nations
UNESCO	United States Educational, Scientific and Cultural Organisation
USGS	United States Geological Services
NOAA	National Oceanic and Atmospheric Administration
NGA	National Groundwater Archive
CCMs	Climate Change Models
SABS	South African Bureau of Standards
SANS	South African National Standards
SDG	Sustainable Development Goals
ACF	Auto-correlation function
CCF	Cross-correlation function

LIST OF ANNOTATIONS AND UNITS OF MEASURE

H_o	Original Hypothesis
H_a	Alternative Hypothesis
l/s	Litres per second
m	Metres
m²	Square Metres
m³	Cubic Metres
m bgl	Metres below ground level
m amsl	Metres above mean sea level
MI/d	Million litres per day
m³/s	Cubic meters per second
Ma	Million Years
Ga	Billion Years

1

INTRODUCTION

1.1 BACKGROUND

South Africa is regarded as a water stressed and semi-arid country with an average rainfall of 860 mm per annum (Botai, et al., 2018; Pietersen, et al., 2011). Globally, groundwater makes up 1.69% of all water available and 30.1% of freshwater (Figure 1-1). Half of the global population relies on groundwater for domestic and agricultural purposes (Van Vuuren, 2017; UNESCO, 2015).

Groundwater further contributes to the formation of “groundwater dependent ecosystems (GDEs)” which are defined as ecosystems that require the availability of groundwater for prolonged periods to sustain their ecological functioning (Murray, et al., 2008; WRC, 2002). In South Africa, groundwater contributes about 40% to rivers, whilst 15% is used for domestic use. South Africa has further identified groundwater as a strategic resource which is vital for ensuring that needs of rural communities and food supply are met (Pietersen, et al., 2011).

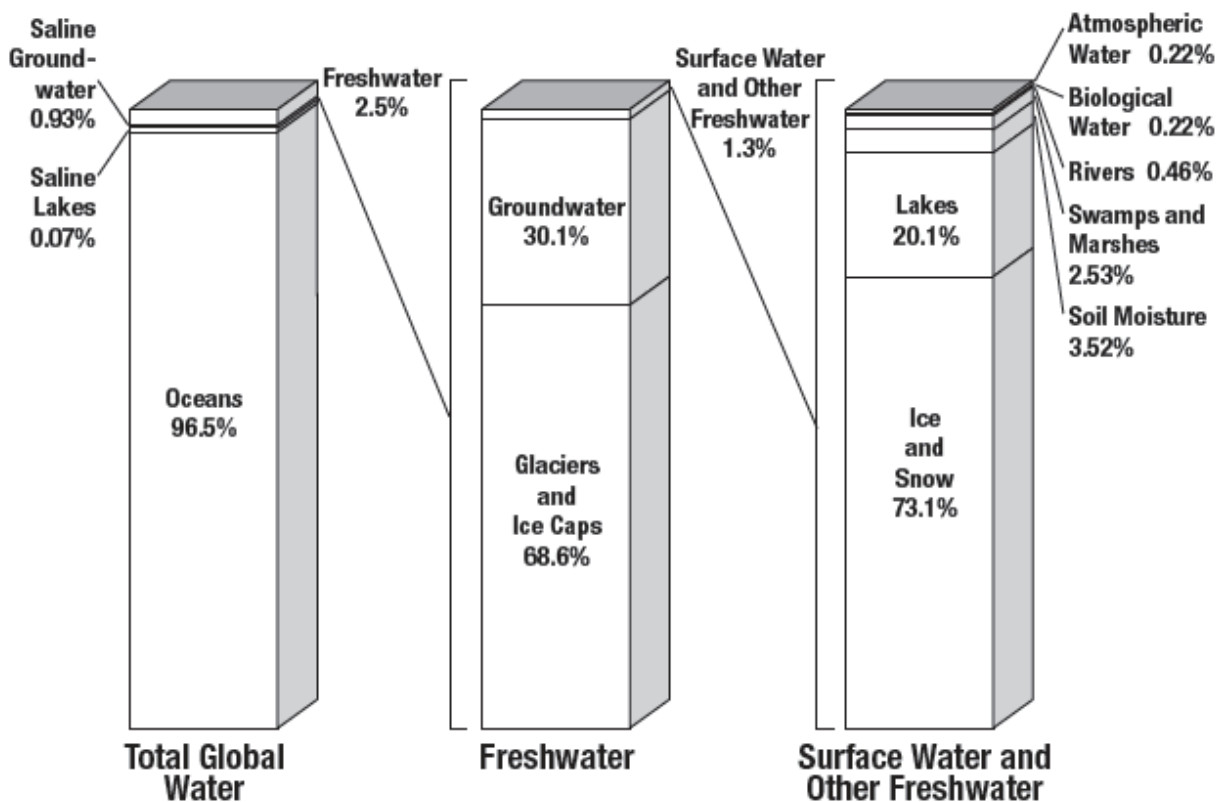


Figure 1-1: Distribution of global water resources (Van Vuuren, 2017)

The City of Tshwane (CoT) Metropolitan Municipality in South Africa uses ~742 Ml/day of water, and of which ~57 Ml/day (7.7%) is derived from groundwater sources. The Fountain East and West Karst aquifer compartments are the main source of the Upper and Lower Fountain Valley springs which supply fresh water to the Pretoria CBD of the CoT. The springs also sustain the ecosystem of the Apies River (Dippenaar, 2013). The combined average flow rate of the springs was reportedly 250 l/s (21.6 Ml/day) and is strongly influenced by surface recharge (Vegter, 1995).

The hydrochemistry and hydrogeological setting of the Fountain East and West Karst aquifer compartments have extensively been studied by authors such as Naidoo (2014), Dippenaar (2013) and Vegter (1995). However, an understanding of the potential impact of spring discharge and water availability was not studied in detail.

Naidoo (2014) highlighted an erratic pattern in groundwater discharge rates of the Lower Fountain spring from July 2011 and October 2011. The erratic discharge rates measured as groundwater discharge at the spring were initially suspected to be associated with groundwater abstraction in the vicinity of the springs. However, the results of the desktop assessment of available boreholes showed an absence of recently registered boreholes near the Lower Fountain spring (Naidoo, 2014).

The purpose of this study was to assess the potential cause of erratic discharge rates observed within the Lower Fountain spring through the development of a detailed conceptual model and statistical analyses.

1.2 MOTIVATION OF THE STUDY

Naidoo (2014) conducted a study on the hydrogeological characterisation of the Fountain East and West Karst Aquifer Compartments, specifically on the hydrochemical characterisation of the compartments. The study indicated a variation between the water levels in the compartments.

The average water levels varied by ~8.5 m with the west compartment showing deeper water levels compared to the east compartment, whilst changes in water levels between gauging events was ~0.5 m. The regional groundwater flow direction of the two compartments is from south to north, while local variations were observed through the correlation of water levels with topography (Naidoo, 2014).

The hydrochemistry of the springs is similar and of Ca(Mg)-HCO_3 (Calcium, Magnesium Bicarbonate) signature which indicates the dominance of Ca and Mg cations with HCO_3 anions associated with fresh recharge from rainfall (Naidoo, 2014).

The study presented erratic springs discharge flows, specifically within the Lower Fountain spring (Figure 1-2). The Upper Fountain spring indicated higher average discharge rates from the dry season (i.e., April-September) onwards compared to the Lower Fountain spring. The Lower Fountain spring indicated monthly erratic spring discharge rates from the dry season (i.e., April-September) onwards (Naidoo, 2014).

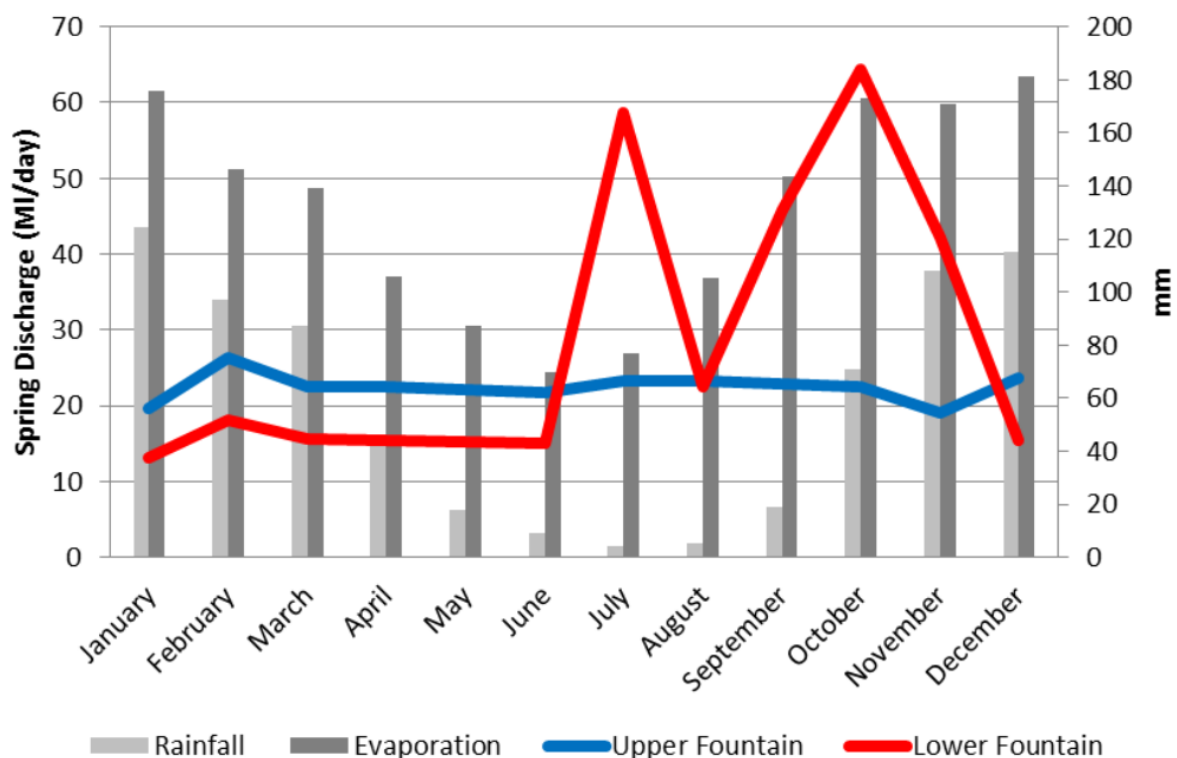


Figure 1-2: Spring hydrographs of the Lower and Upper Fountain recorded between 2011-2012 (Naidoo, 2014)

The varying spring discharge rates which are not causally related to rainfall were attributed to extraneous recharge especially since abstraction boreholes were not identified within the vicinity of the springs (Naidoo, 2014). The analyses of the isotope data did not clearly indicate the source of recharge to the springs (i.e., Pretoria area or a different area). The ratio of isotope oxygen (δO^{18}) and deuterium (δH^2) plotted slightly above the local meteoric water line (LMWL) of the Pretoria area.

The isotope data also indicated a high degree of fractionation suspected to be associated with extraneous recharge or recharge rates as a function of soil infiltration rates due to texture (coarse-grained and fine-grained soils) (Naidoo, 2014).

The aim of the work by Naidoo (2014) was to conduct a hydrochemical characterisation of the Fountain East and West karst aquifer compartments, and thus did not further investigate the spring discharge rates and water availability within the Fountain East and West karst Aquifer Compartments.

The work conducted by Naidoo (2014) recommended that a detailed investigation into the potential cause of erratic spring flow of the Lower Fountain Spring be conducted as there was no evidence of active groundwater abstraction identified.

The potential recharge zones and implications thereof on the response of the springs, the storage, interchange between matrix and karst conduits (i.e. storage and release mechanisms), storage and residence times, including the influence of major land use change and construction activities where large amounts of groundwater are abstracted, such as the Gautrain rail loop on spring discharge rates were not evaluated.

The research to be conducted thus continues this work to assess the potential cause of the erratic spring discharge rates observed within the Lower Fountain spring, by the development of a detailed conceptual model and statistical analyses to understand the groundwater flow.

An understanding of groundwater flow mechanisms in the Fountains Karst Compartments is considered important to understand as this will assist with CoT to estimate the water availability associated with aquifer and improve the security of water supply to the Pretoria CBD, which relies on water from the Fountains Karst Compartment. The ecosystem of the Apies River relies on the constant supply of water from the springs, and it is therefore important to understand if the flow is affected or not, to ensure measures are put in place to ensure that the constant supply of water to the Apies River and its ecosystem are not affected.

1.3 AIMS AND OBJECTIVES OF THE STUDY

The aim of the study is to investigate the release mechanisms of groundwater within Fountain East and West Compartments (referred herein as “the study area”) and assess possible causes of erratic discharge rates within the Lower Fountain spring. The following actions will be taken:

- Collate and organise groundwater levels, spring hydrographs and climatic data of the Lower and Upper Fountain springs;

- Conduct mathematical and statistical assessments to assess groundwater release mechanisms from the karst compartments;
- Conduct a borehole density assessment within the Fountain East and West Karst Compartments to assess whether higher groundwater abstractions could be the cause of erratic spring flows within the Lower Fountain Spring; and
- Establish a detailed conceptual model of the Fountain East and West Karst Aquifer Compartment to characterise the aquifer and hydrogeological flow regimes.

The study is considered to be aligned with the United Nations (UN) Sustainable Development Goals (SDGS) 6 (clean water and sanitation) and 15 (life on land) shown in Figure 1-3. SDG 6 deals seeks to ensure that there is safe and sustainable management of water, including sanitation for everyone (United Nations, 2024). This study aims to address the requirements of SDG6 by assessing how groundwater within the Fountains Karst Compartments flows, which will assist the CoT to gain an understanding of when to optimise the supply from the springs as it supplies Pretoria CBD (Dippenaar, 2013).

The SDG 15 deals with the protection, restoration, and promotion of sustainable use of terrestrial ecosystem (United Nations, 2024). The Apies River has an ecosystem which relies on the constant supply of water from the Fountains Springs (Dippenaar, 2013). It is therefore important to understand whether the supply to the Apies River could be affect over time to pave way for the managing authority (CoT and Department of Water and Sanitation) to put more protection measures in the future and consider the Apies River when sourcing water from the springs to supply the Pretoria CBD.



**Ensure availability
and sustainable
management of water
and sanitation for all**



**Protect, restore and promote
sustainable use of terrestrial
ecosystems, sustainably
manage forests, combat
desertification and halt and
reverse land degradation and
halt biodiversity loss**

Figure 1-3 The United Nations' Sustainable Development Goals developed to guide member states when framing their agenda and political policies (United Nations, 2024)

1.4 RESEARCH METHDOLOGY

1.4.1 DATA COLLECTION AND SOURCES

To characterise the Fountain aquifers, a collection of groundwater monitoring data, hydrochemistry data, geological logs, hydrogeological parameters of the different lithological units will be collated and compared to data used by Naidoo (2014). The data will be assessed for completeness and representativity. The study will rely on both quantitative and qualitative geological, climatic and hydrogeological data, which will be sourced and collated from various public entities, such as the Department of Water and Sanitation (DWS), CoT, South African Weather Services (SAWS) and Council for Geoscience (CGS).

The groundwater monitoring data, lithological logs and hydrochemistry data of the aquifer will be sourced from the National Groundwater Archive (NGA) and Water Use Authorization and Registration Management System (WARMS) managed by the DWS.

The spring discharge rates will be sourced from the Water division of the City of Tshwane who is the sole custodian of the data, and the rainfall data of a weather station within the Lower and Upper Fountain Aquifer will be sourced from the SAWS. The timelines of the meteorological data and groundwater monitoring data will be dependent on the available spring discharge rate data.

1.4.2 MATHEMATICAL AND STATISTICAL ASSESSMENTS

Firstly, the groundwater level data will be compared to rainfall data of similar period together with spring discharge to assess if direct correlation between the data exists. The Reynolds numbers of the Upper and Lower Fountain springs will be estimated to determine the groundwater release mechanisms (i.e., conduit or matrix flow) and implications thereof on the spring discharge rates. Furthermore, a comparison of cumulative rainfall and spring discharge will be conducted to assess the influence of rainfall on spring discharge within the Upper and Lower Fountain Springs. The statistical method that will be used includes auto-correlation/cross-correlation of monthly rainfall (as input) and spring discharge (assumed output).

The correlation of spring discharge and hydraulic head difference within monitoring wells installed within the Fountain East and West Compartments will be conducted to assess the prevailing flows which will give an indication of potential causes of varying spring discharge within the Upper and Lower Fountain Aquifer. The characteristics of the springs and well hydrographs will be assessed to understand the response of the karst aquifer and springs to recharge as a function of rainfall intensity.

1.4.3 BOREHOLE DENSITY ASSESSMENT

To further assess possible causes of erratic spring discharge of the Lower Fountain Spring, a query of the Water use Authorization and Registration Management System (WARMS) databases will be conducted to assess the borehole density within the Fountain West Karst Compartment relative to the Fountain East Karst Compartment as it is expected that higher borehole density will alter the natural flow of groundwater within the karst compartments.

1.4.4 SPRING DISCHARGE AND CHANGES IN LAND USE

To further assess possible causes of erratic spring discharge of the Lower Fountain Spring, a time-series analyses of Google Earth® imagery, coinciding with the available spring discharge data will be conducted to assess infrastructure development on the Lower and Upper Fountain Karst Compartments. Meyer (2014) highlighted the possibility of changes in land affecting groundwater recharge due to leaking water pipes, sewage pipes and construction of dense infrastructure resulting in increased run-off and reduced groundwater recharge.

1.4.5 CONCEPTUAL MODEL

A three-dimension conceptual model showing key aquifer parameters, boundary conditions, geological structures and aquifer characterisation and recharge zones will be formulated to assess potential areas of influence of the Lower Fountain Aquifer. The conceptual model will also include the degree of karstification and dominant flow conditions (laminar or turbulent) within the compartments and influence thereof on the spring discharge of the Upper and Lower Fountain springs.

1.5 STRUCTURE OF THE DISSERTATION

Chapter 1: The chapter presents overall introduction and motivation of the study. The aims and objectives of the study as well as the research methodology are outlined.

Chapter 2: The chapter outlines a theoretical review of the formation of karsts across the globe and in South Africa, hydrogeology of karst aquifers and methods of quantifying the flow of groundwater in karst aquifers.

Chapter 3: The chapter discusses the data collection methods relied upon for the study.

Chapter 4: The chapter includes a description of the environmental setting of the study area, geology, and hydrogeological environment.

Chapter 5: The chapter presents the results of the analyses.

Chapter 6: The chapter provides a discussion and synthesis of the results and presents an updated conceptual site model of the study area which incorporates the results and key information from the discussion and synthesis of the data.

Chapter 7: The chapter provides the conclusions of the study and recommendations for future work.

Appendices: Provide data used for the study and all other information not included in the dissertation.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The chapter includes a review of available literature relating to this study. The literature review includes background introduction on the distribution of karstifiable rocks across the globe and in South Africa, the hydrogeology of karst aquifers and recent methods used to characterise the storage and flow of groundwater in karst aquifers.

2.2 GLOBAL DISTRIBUTION OF KARSTIFIABLE ROCKS

The term karst describes a landscape comprising of caves and widespread underground water system arising from the dissolution of carbonate rocks with distinct lithology and structure (Ford & Williams, 2007). Karst aquifers supply 20 - 25% of the global population with drinking water and covers ~12% of the earth's surface as shown in Figure 2-1 (Radulovic', 2013). Karst environments are often not easily identifiable during hydrogeological investigation which in turn leads to detrimental repercussions during management and impact assessment phases.

The karst system is developed from the dissolution of carbonate and sulphate rocks such as limestone (CaCO_3), dolomite ($(\text{Ca,Mg})(\text{CaCO}_3)$) and gypsum ($\text{CaSO}_4 \cdot \text{H}_2\text{O}$) with secondary fractures that are well developed after metamorphism to form marble (Ford & Williams, 2007). Limestone and dolomite are more common compared to gypsum (Figure 2-1). The weight percentage of carbonate rocks is more than 50% calcite (CaCO_3) or dolomite ($\text{CaMg}[\text{CO}_3]_2$). The interaction of precipitation (H_2O) with carbon dioxide (CO_2) in the atmosphere and organic matter in the soil forms weak carbonic acid (H_2CO_3) responsible for the congruent dissolution of carbonate rocks. The transfer of acidified meteoric water is through:

- Surface depressions characteristic of karst landscapes;
- Subterranean channels, fractures, and conduits; and
- Sink and swallow holes.

A karst system comprises of erosion (chemical and mechanical deposition) and depositional zones (mechanical and chemical deposition). Mechanical erosion involves the flow of water on carbonate rocks where surficial karstification takes place. Deformation due to tectonism leads to the development of fissures and fractures which create preferential pathways for

water to flow into carbonate rocks. The infiltrated water results in further dissolution of carbonate rocks at depth subsequently leading to the formation of karst features such as conduits and caves. The presence of thermal flow at depth leads to hypogenic karstification (Stevanovic, 2015).

2.3 HISTORY OF KARSTIFICATION IN SOUTHERN AFRICA

Southern Africa has approximately 50 000 km² of potentially karst rocks which makes 1.9% of the total host rock cover. The carbonate rocks of Southern Africa formed during the Proterozoic and Tertiary periods. The carbonate rocks of the Proterozoic (ca. 2.2 Ga) comprise of dolomitic limestone whilst Tertiary carbonate rocks comprise of coastal limestones (Eriksson & Altermann, 1998). The dolomitic limestones are highly resistant to alteration but well jointed compared to the coastal limestone and have a chemical signature of CaMg(CO₃)₂.

The lithological units of carbonate rocks include the Chuniespoort and Duitschland Formations of the of the Malmani Subgroup which form part of the Transvaal Supergroup originating within a tidal lagoon environment and comprise of dolomite and chert rich layers. The carbonate rocks of the Campbell Rand Group which forms part of the Griqualand West Formation were deposited within a different basin from the Malmani dolomites but show similar features as the Malmani dolomites (Eriksson & Altermann, 1998).

The thickness of the Malmani Subgroup varies from 200 m to 1 800 m with an average thickness of 1 500 m and is subdivided based on chert content, stromatolite structures and intercalated shale and surfaces of erosion. The varying contents of chert have been attributed to a contrast in depositional environment which differs from subtidal environment (chert poor) to supra to inter-tidal environments (chert rich).

The presence of chert-rich layers exacerbates the dissolution of the host dolomite along joints and bedding plane into high groundwater yielding aquifers with a skeletal structure as shown in Figure 2-2 (Meyer, 2014). Although not structurally deformed, the Pilanesberg aged (1 200 – 1 450 Ma) dykes intrude the Malmani dolomites resulting in the compartmentalisation of the emergent aquifer systems. The micritic sandy coastal limestones are highly susceptible to weathering but poorly jointed compared to the dolomitic limestone (Lee, et al., 2017; Eriksson & Altermann, 1998).

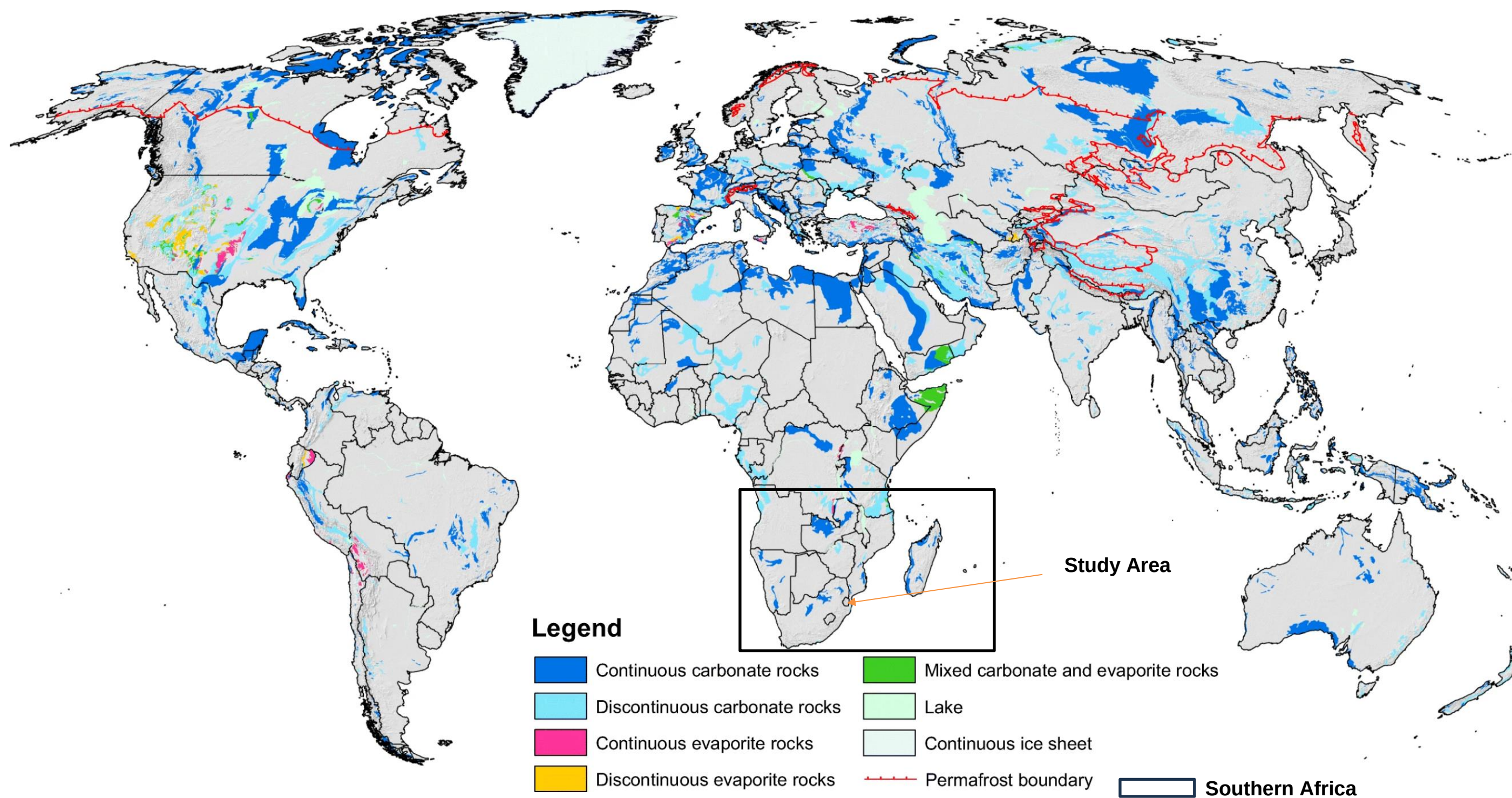


Figure 2-1: Spatial distribution of karstifiable rocks across the globe (Goldscheider, et al., 2020)

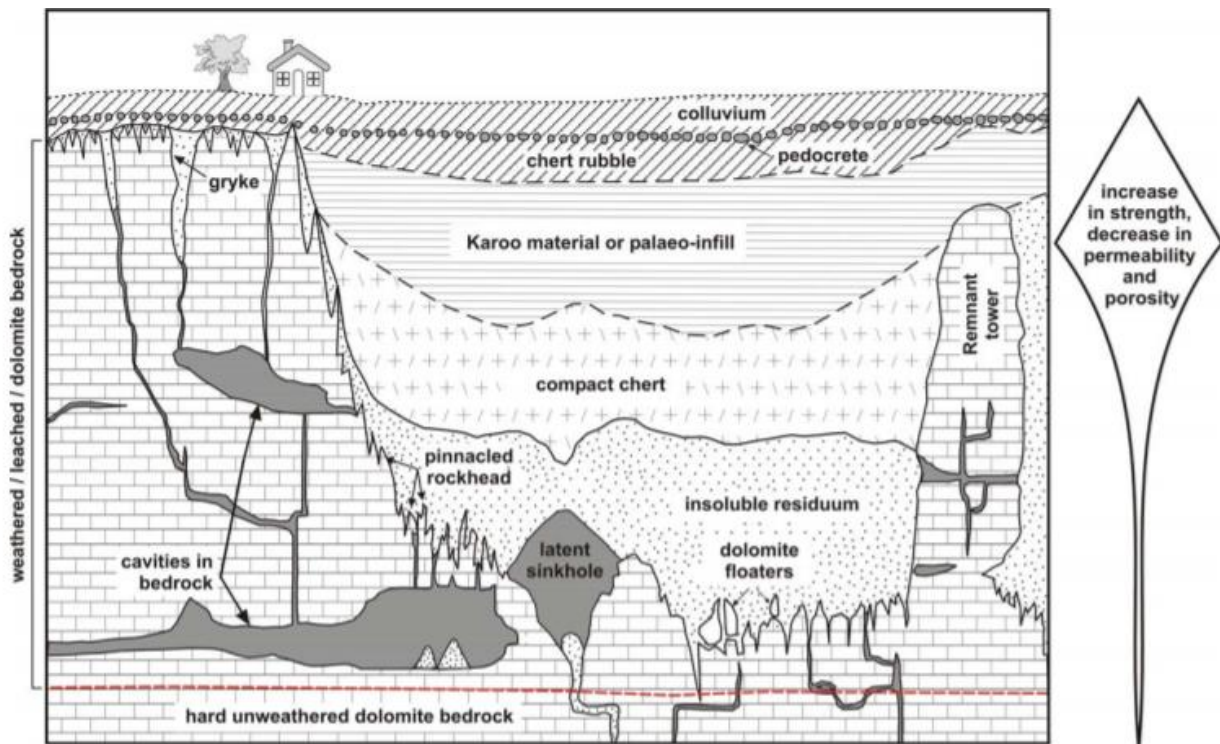


Figure 2-2: Conceptual model of a karst landscape in South Africa (SABS, 2009)

2.4 KARST HYDROGEOLOGY

The recharge of karst aquifers has been characterised into either autogenic or allogenic as shown in Figure 2-3. Autogenic recharge is associated with run-off and dispersed infiltration around and within the karst environment. Losing streams and external run-off outside the karst environment are associated with allogenic recharge.

The epikarst facilitates the redistribution of stored recharge into the conduits and fractures of the karst aquifer. Following redistribution in the epikarst, the flow of groundwater is redistributed through diffuse flow within the matrix (i.e., pores and fractures) or turbulent and rapid flow within the conduits/pipes which have contrasting porosity and hydraulic conductivity (Goldscheider & Drew, 2007). The matrix and conduits of karst aquifers have higher groundwater storage capacities and groundwater residence times are shorter in the conduits compared to the matrix (Olarinoye, et al., 2021).

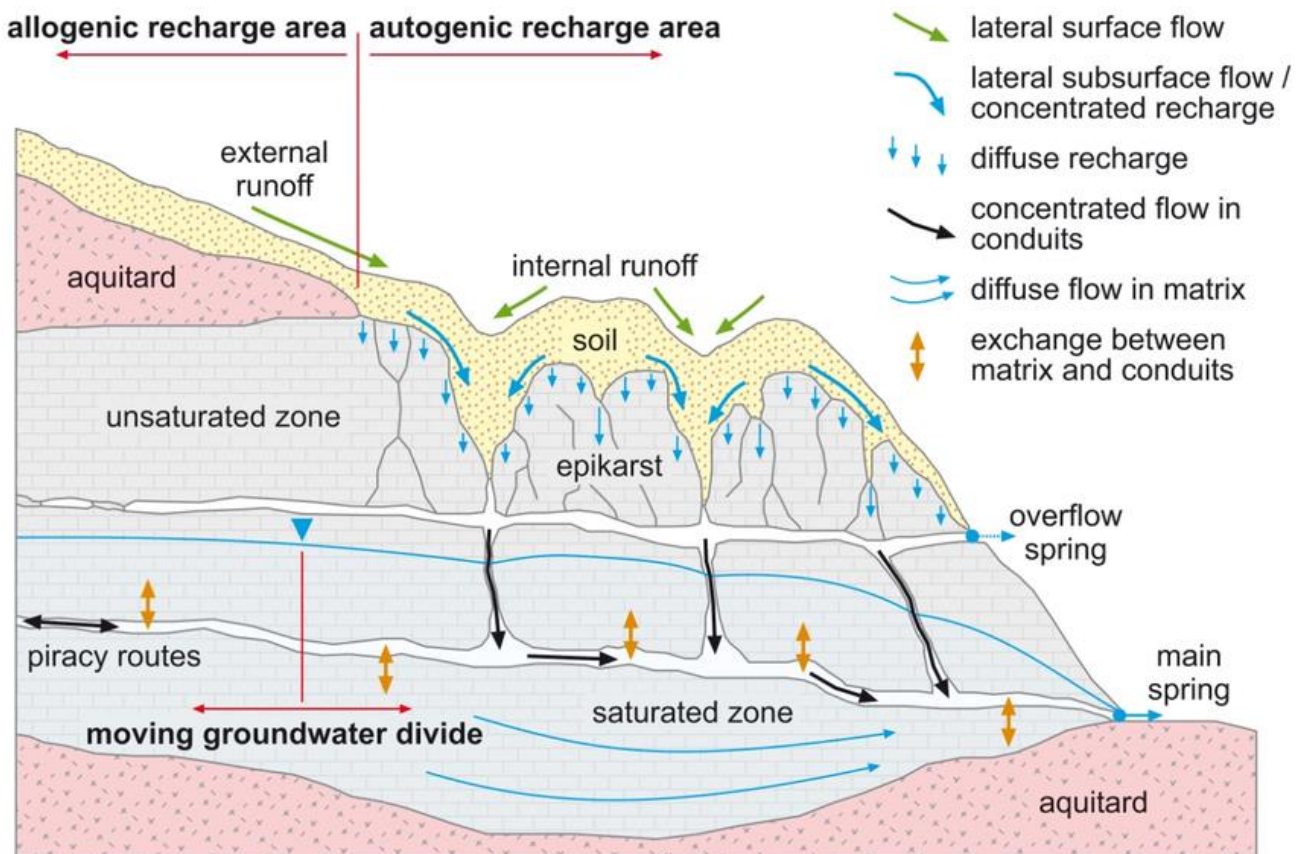


Figure 2-3: Groundwater and Surface water flow regimes of Karst aquifers (Goldscheider & Drew, 2007)

The porosity of karst aquifers varies from primary porosity/matrix porosity associated with voids formed during the precipitation of carbonate rock to secondary porosity/conduit porosity associated with metamorphism and dissolution of carbonate rocks. The flow system of karst aquifers has been observed to transition from unsaturated to saturated and vice-versa over time (White, 2002; Goldscheider & Drew, 2007; Shirafkan, et al., 2021). Hartmann et al. (2013) highlighted the flow dynamics of karst aquifers as being of dual nature.

The varying flow regime are responsible for different pressure gradients observed in karst environments, which control temporal and spatial rate of karst recharge and discharge (Goldscheider & Drew, 2007). The hydraulic conductivity of karst conduits in other study areas has been calculated to be 0.1 m/s whilst hydraulic conductivity of the matrix has been calculated to be 0.001 m/s to 0.1 m/s (Guo, et al., 2021). According to Hartmann et al. (2003) and Shirafkan et al. (2021), the nature of flow within karst aquifers as shown on (Figure 2-3) include:

- Dual infiltration and recharge which varies from slow infiltration on low permeable zones and rapid recharge along grykes;

- Low flow processes along fractures and rapid flow along conduits within the karst aquifer system; and
- Slow seepage discharge from the matrix during the dry season to rapid discharge from the springs during the wet season.

The hydraulic conductivity of karst aquifers is of treble nature (i.e. matrix, fracture and conduit controlled). Low permeability is encountered within the matrix of the carbonate rocks whilst the high hydraulic conductivity which controls the overall conductivity of the karst aquifer is encountered along conduits and fractures (Goldscheider & Drew, 2007).

The flow of groundwater in karst aquifers can vary from laminar flow dominant within the matrix to turbulent flow dominant within well connected large diameter voids and conduits. Laminar flow (i.e., parallel streamlines) is characteristic of viscous forces which exceed shear stress whilst turbulent flow (i.e., non-parallel streamlines or eddies) is characteristic of shear stresses that are greater than viscous forces as shown in Figure 2-5 (Gallegos, 2011).

The Reynolds number (Re) is important in assessing the ratio of fluid inertial forces to viscous forces (Shoemaker, et al., 2008). The Reynolds number (Equation 1) of flow regimes is important in determining whether flow is laminar or turbulent (Ghasemizadeh, et al, 2012). Although the Reynolds number describes flow in a pipe, Equation 1 can be used to assess the nature of flow in karst conduits, considered to behave as pipes. The diameter of the pipe as presented in Equation 1 represents the diameter of the conduit in a karst aquifer.

$$Re = \frac{\rho v D}{\mu gc} \quad \text{Equation 1}$$

where:

Re = Reynolds Number (unitless)

ρ = fluid density (kg/m^3)

v = average velocity (m/s)

D = diameter of conduit (m)

gc = Gravitational Constant ($N.kg^{-2}m^2$)

A Reynolds number of less than 1 to 10 indicates laminar flow where Darcy's law applies, whilst a Reynolds number of greater than 10 indicates turbulent flow where Darcy's law does not apply (Wang, et al., 2019). The critical Reynolds number (N_{Re}) indicates conditions where flow transitions from laminar to turbulent flow ($10 < Re > 10$) as shown in Figure 2-4.

The N_{Re} of porous media ranges from 1 to 10. Laminar flow is dominating where of elevated frictional and surface tension forces along the fluid and matrix interface exists (Worthington & Soley, 2017; Shoemaker, et al., 2008).

The streamlines of laminar flow as shown in Figure 2-5 are parallel due to shear stress being greater than viscous forces. Turbulent flow dominates due to reduced frictional and surface tension forces along the fluid-matrix interface due to the presence of voids or conduits which restrict the flow of fluid at the conduit/ void walls (Shoemaker, et al., 2008).

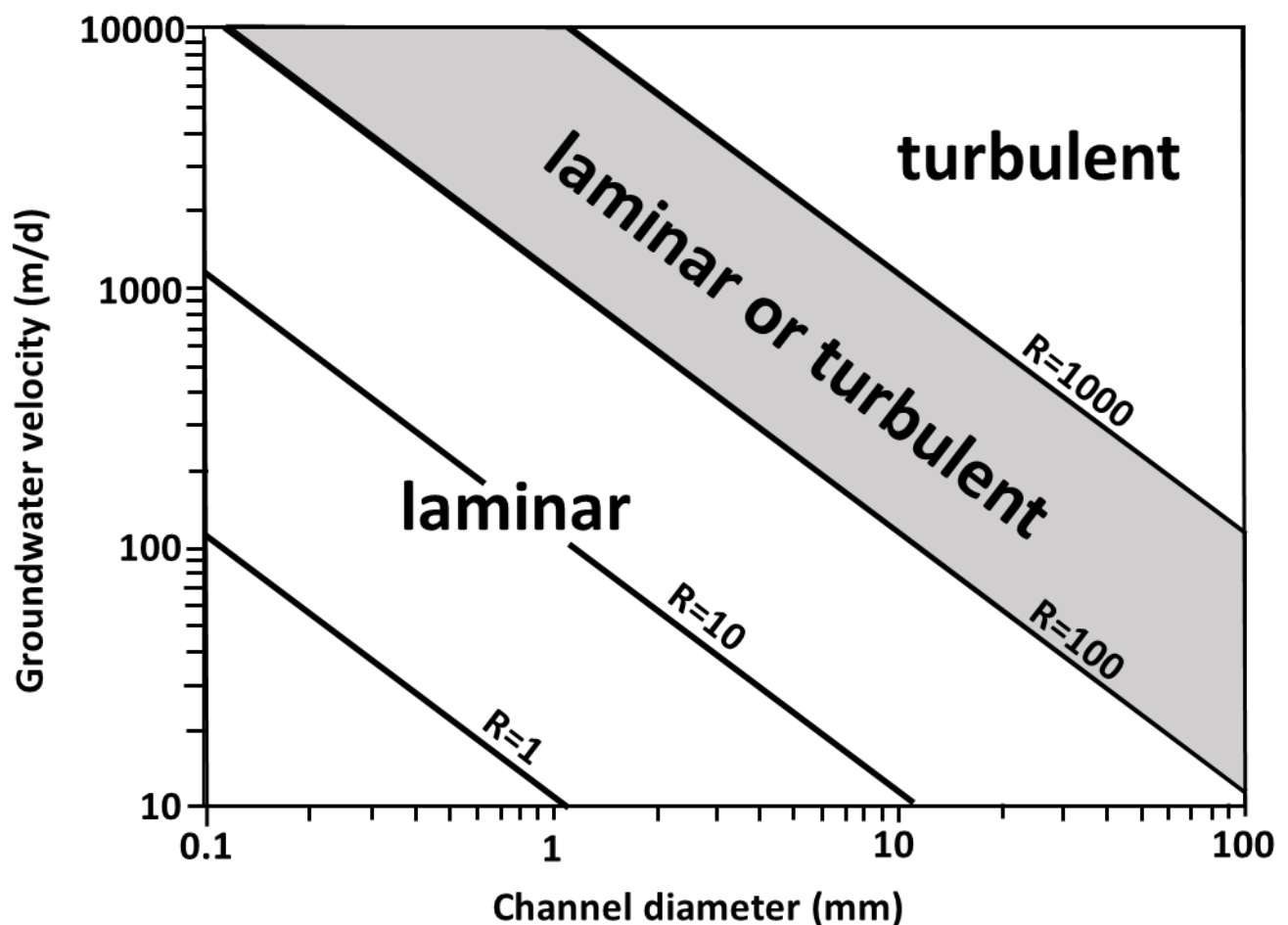


Figure 2-4: Representation of Reynolds numbers indicative of turbulent and laminar flow at given groundwater velocity and channel/conduit diameter (Worthington & Soley, 2017)

The streamlines of turbulent flow as shown in Figure 2-5 are tortuous and form eddies due to viscous forces being greater than shear stress. Laminar flows are common in porous media due to low groundwater velocities which follow Darcy's law.

The presence of voids and conduits in carbonate rocks results in conditions that do not follow Darcy's law and therefore the head loss within voids and conduits of karst aquifer is calculated using the Darcy-Welsbach equation presented as Equation 2 (Giese, et al., 2018;

Goldscheider, et al., 2020). The rapid recharge of karst aquifers can result in abrupt changes of hydrochemistry, water levels and spring discharge rates and thus karst aquifers require event monitoring as opposed to traditional regular monitoring especially for pollution assessment studies (Goldscheider & Drew, 2007). As described for Equation 1, the parameters in Darcy-Welsbach equation (Equation 2) are required to assess head loss in a pipe, which would be represented by conduits in karst aquifer, where the length of the pipe would be similar to the average length of the dominant conduits, and the pipe diameter be equivalent to the diameter of conduits.

$$\Delta h_c = f \frac{\Delta l_p v^2}{2g d\rho} \quad \text{Equation 2}$$

where:

Δh_c = head loss in a conduit or void

Δl_p = length of the conduit

f = flow frictional factor

g = gravitational acceleration

$d\rho$ = conduit diameter

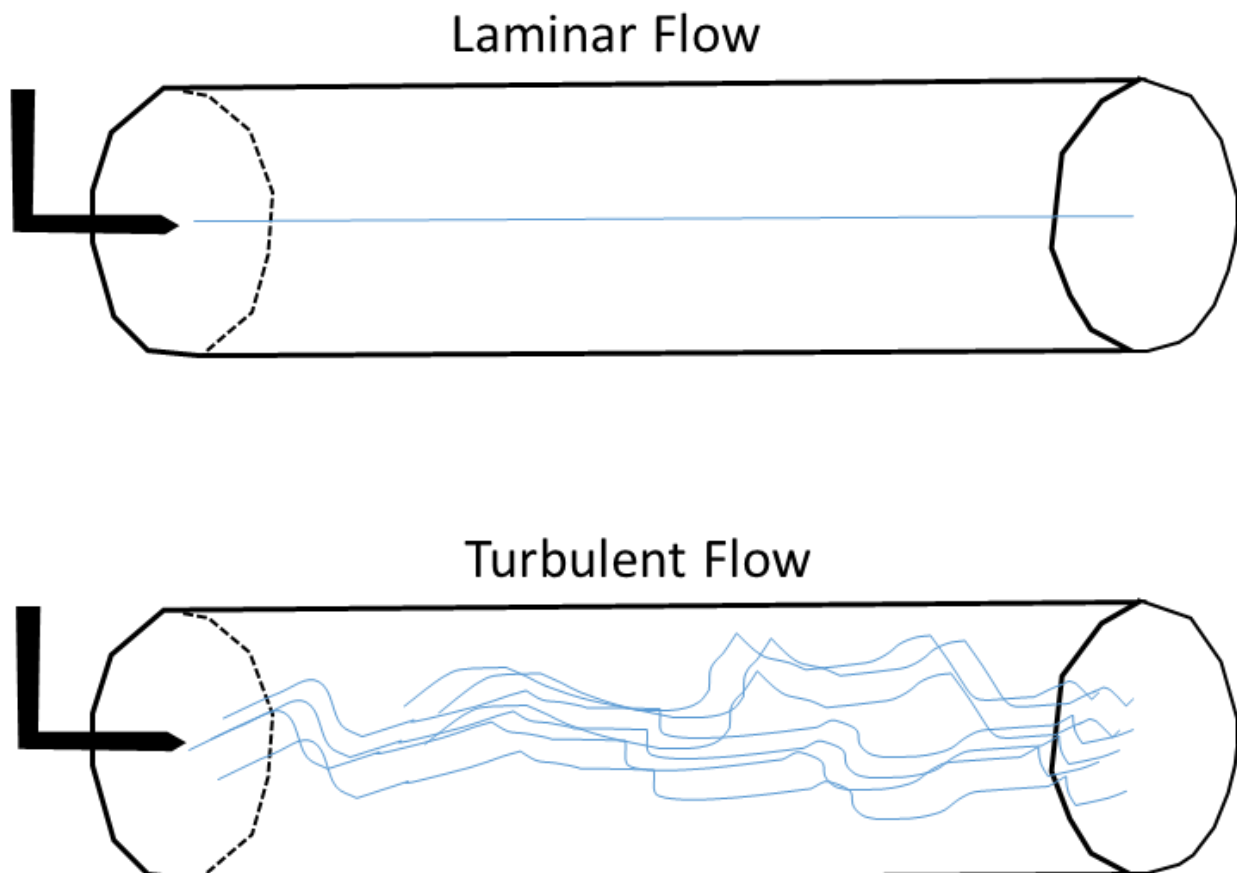


Figure 2-5: Graphical representation of laminar flow (matrix flow) and turbulent flow (fracture and conduit flow) Modified from: (Gallegos, 2011)

2.5 METHODS FOR ASSESSING THE HYDROGEOLOGY OF KARST AQUIFERS

Several methods can be used to assess the flow of groundwater and structure of karst aquifers. The methods include:

- Tracer tests to delineate inter connectivity between conduits acting as preferential pathways (Varnavina et al., 2019; KARMA, 2021);
- Geological mapping to identify surface outcrops, surface geological structures, changes in vegetation, geomorphic features such as sinkholes (Ren et al., 2021);
- Geophysical survey to map degree of karstification, saturated zones and lithology (Varnavina et al., 2019; Ren et al., 2021);
- Borehole drilling following geophysical survey to physically verify the lithology, depth, degree of weathering and dissolution structures (Ren et al., 2021)
- Hydrochemistry (Naidoo, 2014; Ren et al., 2021);
- Isotope assessment to identify areas of recharge including source of recharge and influence of climate change (Sappa et al., 2018; Naidoo, 2014; Iacurto et al., 2021);
- Remote sensing to map regional lithology, land cover changes including geomorphic features such as sinkholes and dolines (Weary & Doctor, 2014; Pisano et al., 2022);
- Statistical and mathematical analyses of spring discharge data, water level data and rainfall data including hydrogeochemical parameters of karst springs (Olarinoye, et al., 2021; Brkić, et al., 2018);
- Development of a water balance to estimate recharge into the aquifer (Jukić et al., 2021). and
- Numerical modelling of groundwater flow in karst aquifers (Duran & Gill, 2021; Gallegos, 2011).

The development of a water balance model was considered in this study to estimate the recharge of groundwater into the karst aquifer. However, the limited amount of data available for the study area, such as lack of sufficient information on inflows from streams, surface water features within each compartment, monthly groundwater abstraction volumes, regional flows and information on groundwater exchanges between the Fountains Karst Compartments and adjacent compartments, through piracy routes as noted by Jukić, D et al. (2021) and observed from the available data, meant a water

balance model of the study area would be unreliable .An in-depth overview of recession curve and correlation analyses which are the selected method of investigation for the research is presented in subsections below.

2.5.1 KARST SPRING HYDROGRAPH ANALYSES

The hydraulic behaviour of spring flow from karst aquifers has been evaluated through inexpensive spring hydrograph analyses/recession curve analyses and recently in the 20th century, through Cross-Correlation Function (CCF) and Auto-Correlation Function (ACF) which focus on time series analyses (Olarinoye, et al., 2021; Brkić, et al., 2018). Spring hydrograph analyses, as shown in Figure 2-6, is important in differentiating spring flows from laminar (slow/baseflow) and turbulent (rapid flow) flow regimes. Laminar flow is associated with flow within the matrix, whilst rapid flow is associated with flow within conduits of karst aquifers. Although differentiated into two flow regimes, studies have shown that the flow regimes of other karst aquifers can be of dual nature where a combination of matrix and conduit flow is observed (Brkić, et al., 2018).

The rapid response of karst aquifers to rainfall as indicated by steep spring hydrographs in Figure 2-6 (b) has been found to be associated with intensive rainfall infiltrating into the conduits of the karst aquifer system where flow is predominantly turbulent (Fiorillo & Doglioni, 2010). The slow release of water from the spring as observed from a less steep semi-logarithmic hydrograph (slow) as shown in Figure 2-6 (a) has been attributed to the released of water from the matrix, fissures, and smaller conduits where flow is predominantly laminar.

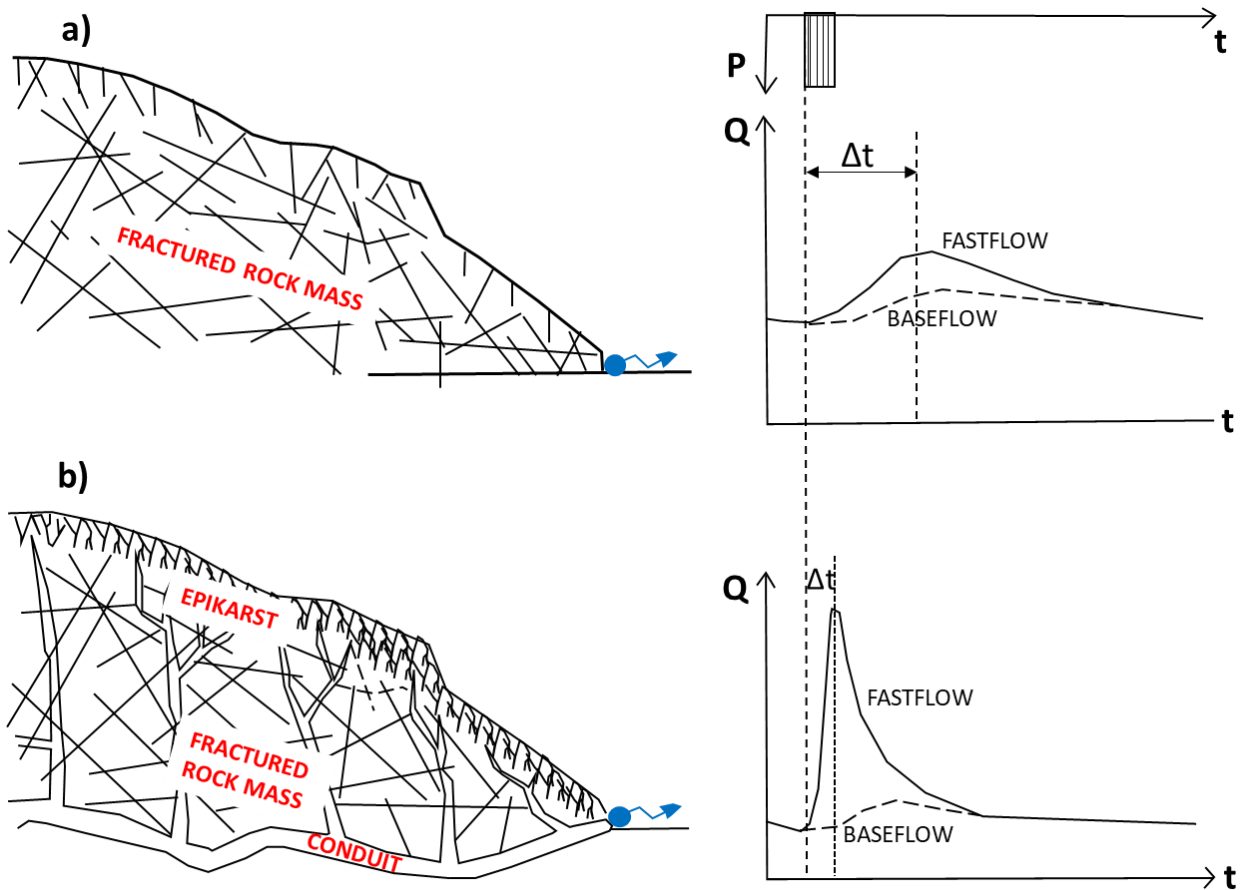


Figure 2-6: Characteristics of hydrograph within a spring releasing water from (a) fissure aquifer and (b) karst aquifer (Brkić, et al., 2018)

A steeper semi-logarithmic hydrograph indicates more turbulent flow associated with the release of groundwater from conduits (fast flow). Although flow within karst aquifers is either turbulent, laminar, or dual, further subdivision includes matrix-restrained flow and conduit-influenced flow regime. Spring hydrographs have been described as powerful tools to differentiate flow of karst aquifers since the conduit network is almost always unknown (Fiorillo & Doglioni, 2010; Olarinoye, et al., 2021).

The analyses of linear storage (release of groundwater from matrix of carbonate rocks) from recession curves of spring hydrographs have been conducted using the Maillet (1905) exponential formula (Equation 3). Guo et al. (2021) and Torresan et al. (2020) indicated that higher recession coefficients with an order of magnitude of 10^{-1} represent rapid conduit flow, whilst recession with an order of magnitude of 10^{-2} represent dual flow (matrix and conduit flow), and recession coefficients with an order of magnitude of 10^{-3} represent slow diffuse flow.

The subdivision of the recession curve into different segments has been shown to yield results with more resolution which can be used to assess the behaviour of different reservoirs in karst aquifers (Torresan, et al., 2020).

$$Q_t = Q_0 e^{-\alpha(t-t_0)} \quad \text{Equation 3}$$

where:

Q_t = is discharge rate associated with baseflow along the recession curve at time t

Q_0 = is discharge rate at the beginning of the recession curve at time t_0

α = is the recession coefficient/ slope of the recession curve

t = time at Q_t

t_0 = time at the beginning of the recession curve

The Maillet equation can be plotted on a log-log graph to determine the recession coefficient using Equation 4 (Kresic & Bonacci, 2010).

$$\log Q_t = \log Q_0 - 0.4343 \times \alpha \times \Delta t \quad \text{Equation 4}$$

where:

$\Delta t = t - t_0$

Dewandel et al. (2003) indicated that although the Maillet equation is more practical to apply when determining recession coefficients of karst springs, the quadratic Boussinesq (1904) equation presented as Equation 5, provides an exact analytical solution of flow through karst aquifers.

$$Q_t = \frac{Q_0}{(1 + \alpha t)^2} \quad \text{Equation 5}$$

An understanding of the Degree of Karstification (DK) is important when developing numerical models of karst aquifers, which can either be equivalent porous models or conduit-based models (Akratos, et al., 2018). The analyses take the rising limb, peak and recession data of the hydrographs into consideration as indicated in Figure 2-7, using the Rashed (2012) equation (Equation 6):

$$DK = \frac{Q_{max} t_{event}}{Q_{min} t_{Peak}} \quad \text{Equation 6}$$

where:

Q_{max} = peak spring discharge (Q_B)

t_{event} = total time of flow from rising limb to baseflow of the recession curve ($t_C - t_B$)

Q_{min} = minimum spring discharge/baseflow before rising limb (Q_A)

t_{peak} = time at peak spring discharge (t_B)

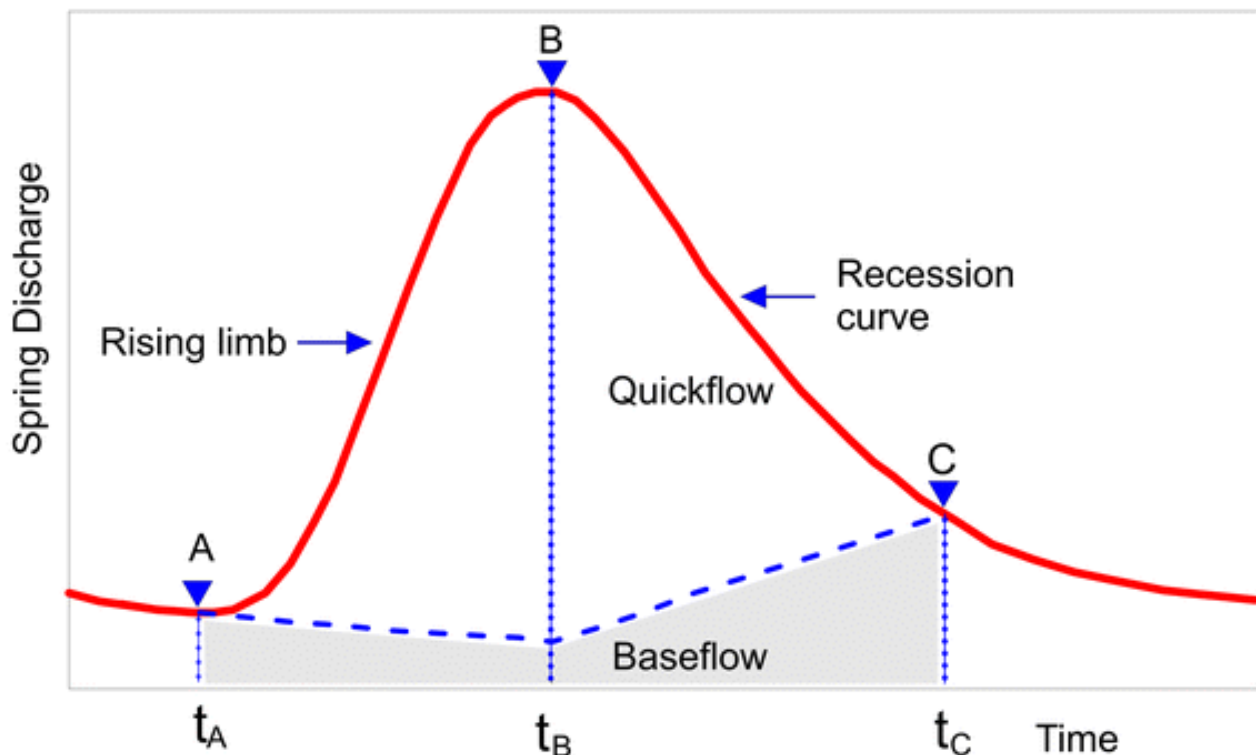


Figure 2-7: Characteristics of spring hydrograph showing parameters required to determine the degree of karstification (Akratos, et al., 2018)

2.5.2 TIME SERIES ANALYSES OF KARST SPRING DISCHARGE RATES

The application of a water balance approach to assess spring discharge rates and water availability has been found to be ineffective; while data-oriented approaches such as machine learning and numerical modelling have shown promising results (Olarinoye, et al., 2021).

Although the dominant flow process can solely be determined from recession curve analyses, the CCF and ACF have been relied upon to further understand the groundwater flow reserve and degree of karstification based on auto- and cross-correlations of variables such as spring discharge, electrical conductivity, temperature, and suspended sediments in relation to recharge within karst aquifers (Sarker & Fryar, 2022).

2.5.2.1 CROSS-CORRELATION (CCF) AND AUTO-CORRELATION (ACF) ANALYSES

The presence of a discharge point in the form of springs where the delayed response of the aquifer following meteoric recharge can be measured has been leveraged to conduct comparison analyses (Guo, et al., 2021). A study conducted by Guo et. al. (2021) applied CCF and ACF to successfully deduce the cause of varying spring discharge rates within the

Pyrean karst aquifers located between France and Spain, where varying spring flows were found to be attributed to varying degrees of karstification and groundwater storage capacities (Guo, et al., 2021).

The ACF has been applied to identify the linear dependency of variables such as precipitation, groundwater levels and spring discharge within a time series, and assess the memory effect of a system as shown by studies conducted by Fiorillo and Doglioni (2010) and Delbart et al. (2016).

The study conducted by Delbart et al. (2016) compared the ACFs of rainfall and water levels within different boreholes installed into a karst aquifer where varying auto-correlation factors were observed for groundwater levels within the different boreholes compared to rainfall as shown in Figure 2-8. The shape of the ACFs of groundwater levels within the different boreholes indicated slow response except for groundwater in one borehole (S5) which had a higher auto-correlation factor, providing evidence for linear relationship between measured water levels and precipitation. The ACFs of the different boreholes indicated two distinct flow regimes for lag times of between 0 to 100 days and 300 to 400 days as shown in Figure 2-8.

Fiorillo and Doglioni (2010) selected cumulative rainfall over pre-selected time intervals for input into the AFC whilst spring discharge was selected as an output of the function to assess the effect of long-term rainfall on spring discharge. The rainfall data studied by Fiorillo and Doglioni (2010) was statistically analysed as processed and unprocessed data, where the latter included the removal of seasonal trends.

In addition, the time intervals of the cumulative rainfall were derived from the application of ACF using descriptive statistical data (10th and 90th percentiles, mean and variance) of the processed and unprocessed rainfall data (Fiorillo & Doglioni, 2010). Although the initial analyses were conducted on unprocessed data, the study indicated that the removal of seasonal and linear trends, yields better correlation in determining the time (time lag, K) required for rainfall to recharge the karst aquifer before the associated springs can flow, where the ACF was calculated using Equation 7 (Li, et al., 2021).

$$r_x(k) = \frac{\frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(x_{t+k} - \bar{x})}{\frac{1}{n} \sum_{t=1}^n (x_t - \bar{x})^2} \quad \text{Equation 7}$$

where:

$r_x(k)$ = cross correlation coefficient
 n = number of samples

x_t = value of the process at time t
 t = discrete time
 $\bar{x}$ = mean
 k = time lag until a selected truncation time

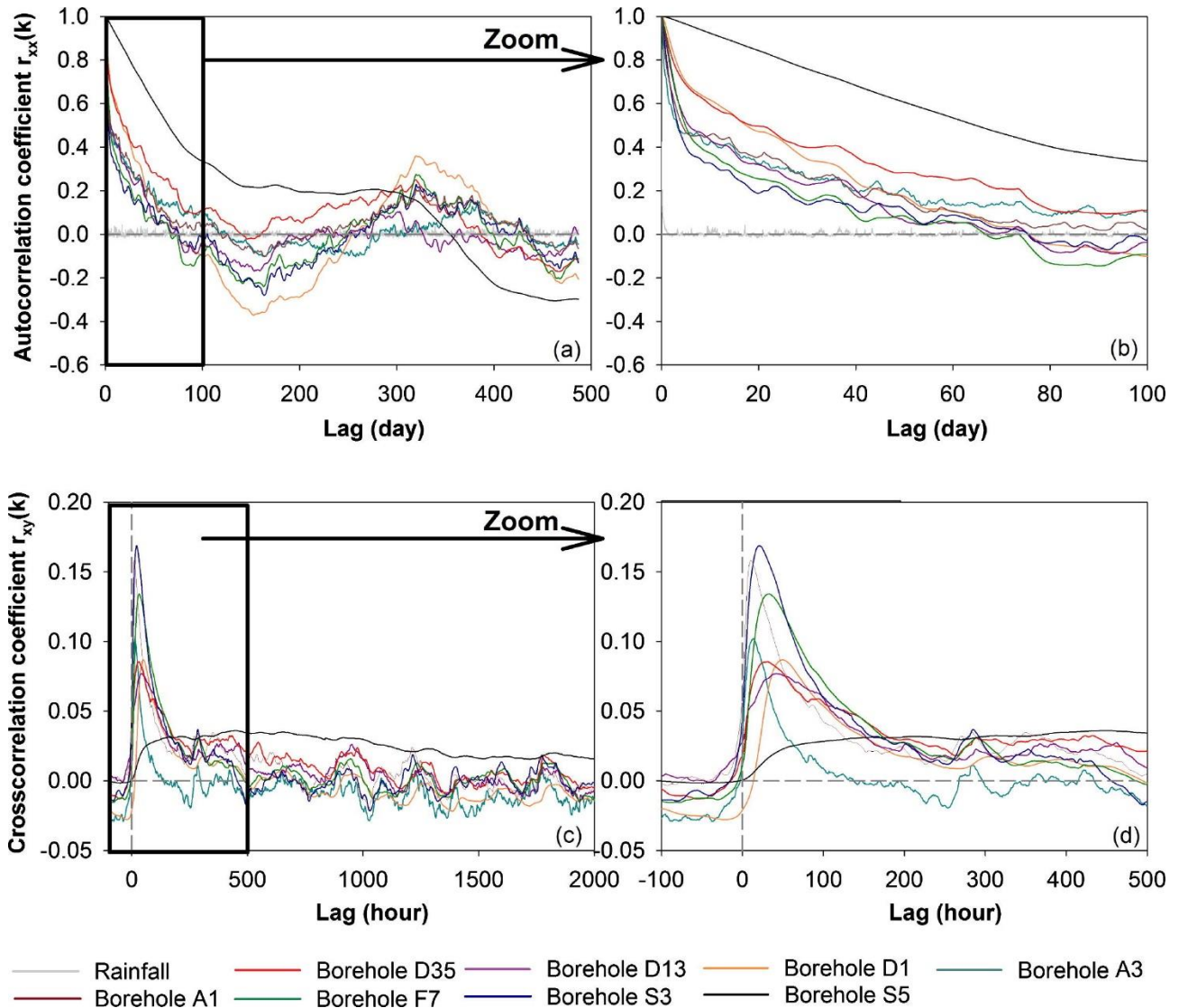


Figure 2-8: Auto-correlation coefficients of rainfall and groundwater levels within different boreholes from Dijon in eastern France (Delbart, et al., 2016)

In addition to the CFA, the CCF was relied upon to identify the relationship between input data (such as rainfall or recharge) against the output data (such as spring discharge) measured over a given time. Greater correlation is indicated by a factor greater than zero and poor correlation is indicated by negative factors; as shown for the relationship between precipitation and physicochemical parameters measured in a karst aquifer in China (Li, et al., 2021; Lyon, 2010).

The calculated CCF shown in Figure 2-9 indicate a response time of 2 days ($r_{xy}(k) = 0.226$) for spring discharge (Q) following recharge (P), whilst for suspended material (SS), a similar

response of 2 days is observed, indicating that following recharge, suspended material will be observed within 2 days as the spring flows. The cross correlation of SS was much sharper than that of Q indicating the disappearance of fine sediments at a particular time.

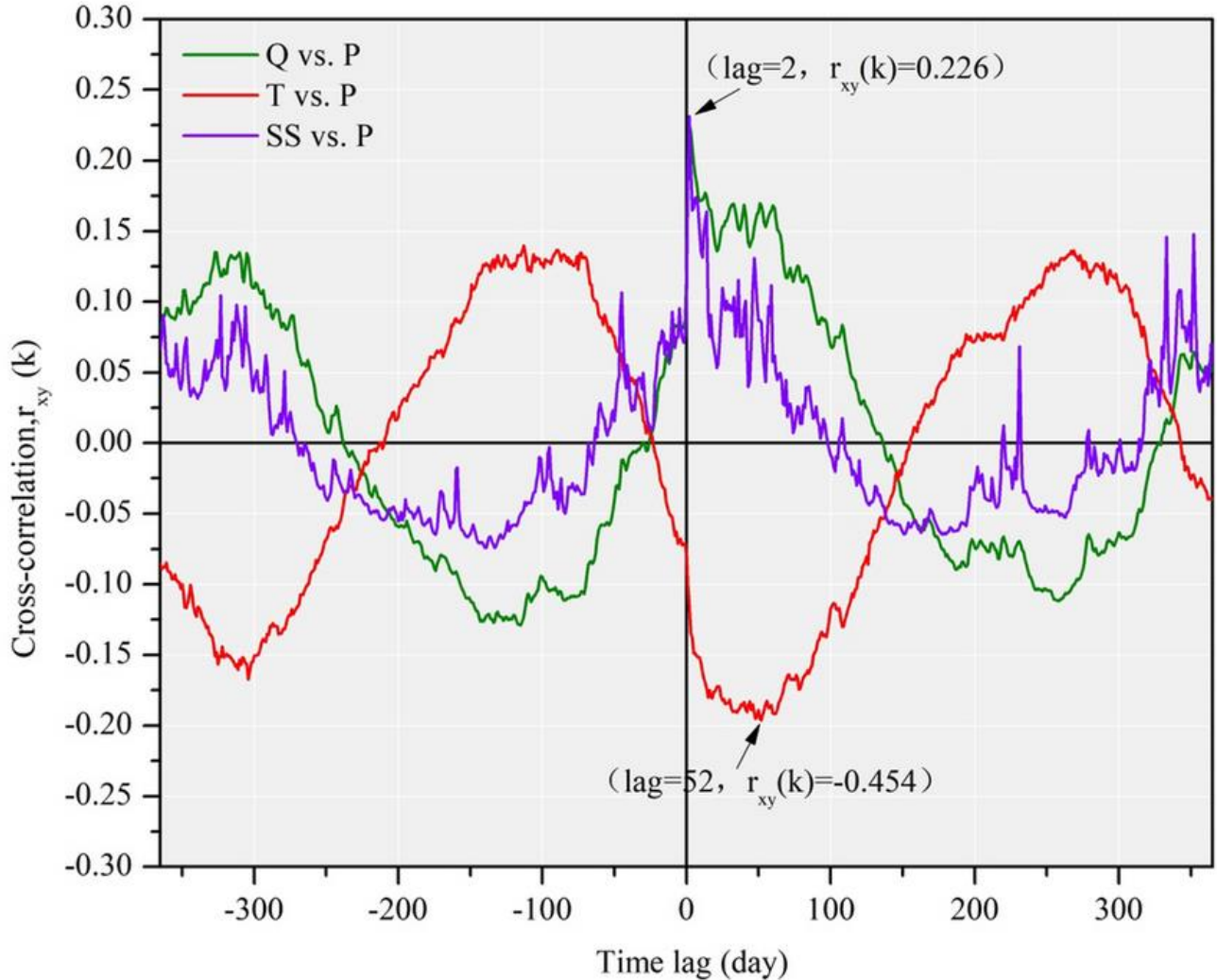


Figure 2-9: Cross-correlation of spring discharge, temperature, and suspended sediments against precipitation of the Nandong Underground River System in the Southern Province of China (Li, et al., 2021)

The CCF is suitable for the characterisation of interrelationship between input and output data series of a time series (Li, et al., 2021). The formula for calculating the CCF is presented as Equation 8 and where the correlogram at lag time K is determined using Equation 8 and correlograms for variable x (e.g., rainfall) and y (e.g., spring discharge) are determined from Equation 10 and Equation 11 (Li, et al., 2021).

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sqrt{C_x^2(0)C_y^2(0)}} \quad \text{Equation 8}$$

where:

$$C_{xy}(k) = \frac{1}{n} \sum_{i=1}^{n-k} (x_t - \bar{x})(y_{t+k} - \bar{y}) \quad \text{Equation 9}$$

$$C_x(0) = \frac{1}{n} \sum_{t=1}^n (x_t - \bar{x})^2 \quad \text{Equation 10}$$

$$C_y(0) = \frac{1}{n} \sum_{t=1}^n (y_t - \bar{y})^2 \quad \text{Equation 11}$$

where:

$\bar{x}$ = mean of time series x

$\bar{y}$ = mean of time series y

$r_{xy}(K)$ = linear cross correlation function

$C_{xy}(K)$ = covariance of time series x and y at time lag K

k = time lag from 0 to m

m = cut-off time

$C_x(0)$ = standard deviation of time series x (e.g. rainfall)

$C_y(0)$ = standard deviation of time series y (e.g. spring discharge)

n = length of the time series

x_t = value of the process at time t

y_t = value of the process at time t

Mangin (1984) recommends that the truncation (m) be taken as 1/3 of the entire dataset.

2.5.3 LIMITATIONS OF RECESSION CURVE ANALYSES, CROSS- AND AUTO-CORRELATION ANALYSES

The application of recession curve analyses in assessing the hydraulic parameters, physical properties, and movement of groundwater in karst aquifers has been found to be less intensive and cheap than the more intensive field exercises such as tracer and pump testing (Ford & Williams, 2007). Recession curve analyses provides insights into the geometry (infiltration, interchange between matrix and conduit, storage) and release of groundwater from karst aquifers solely from temporal discharge and catchment area (Olarinoye, et al., 2021).

Abdin et al. (2021) have shown that the resolution of acquired spring discharge data plays a significant role of the Mean Root Square Error (MRSE) of the simulated spring discharge data using the Maillet's (1905) and Boussinesq's (1877, 1904) equations, where the highest MSREs were observed for data collected on monthly basis, while lower MRSE were

observed for spring discharge data collected daily using both the Maillet and Boussineq equations. Abdin et al. (2021) have acknowledged challenges which have resulted in limited high-resolution data acquisition. The identified challenges includes limited accessibility to the test sites which are only accessible once a month, and the equipment used for collecting telemetry data is not always available.

Abdin et al. (2021) indicated the need to apply auto-correlation and cross-correlation methods to data that is continuous over a period and as such not suitable for data collected over a short period of time which is common for most hydrogeological studies, particularly hydrogeological studies on karst springs. Consequently, recession curve analyses have been found to be more robust when analysing short term spring discharge data compared to auto-correlation and cross-correlation (Abdin, et al., 2021). Akratos et al. (2018), further highlighted the potential ineffectiveness of the cross-correlation function to describe the lag between precipitation and spring response of karst aquifers where flow is dependent on the release of groundwater from the matrix.

The combination of recession curve analyses, CCF and ACF has been vital for the development of conceptual model of karst aquifers as shown by Torresan et al. (2020). The need to filter data of parameters naturally auto-correlated, such as spring discharge data, temperature, and electrical conductivity, was highlighted to ensure that accurate results are determined. The filtering included the application of a simple filter comprising of the difference of one lag between parameters (Torresan et al., 2020).

3 MATERIALS AND METHODS

3.1 INTRODUCTION

The chapter describes the methods and materials used during the study. The source and description of all data and software used to complete time series analyses are described in the section. The data collection exercise of the study focused on gathering publicly available data such as groundwater levels and lithological logs from the National Groundwater Archive (NGA), rainfall data from the South African Weather Services (SAWS) and spring discharge data from the City of Tshwane (CoT) Metropolitan Municipality. A summary of the process flow followed for this study is presented in Figure 3-1 and described in subsections below.

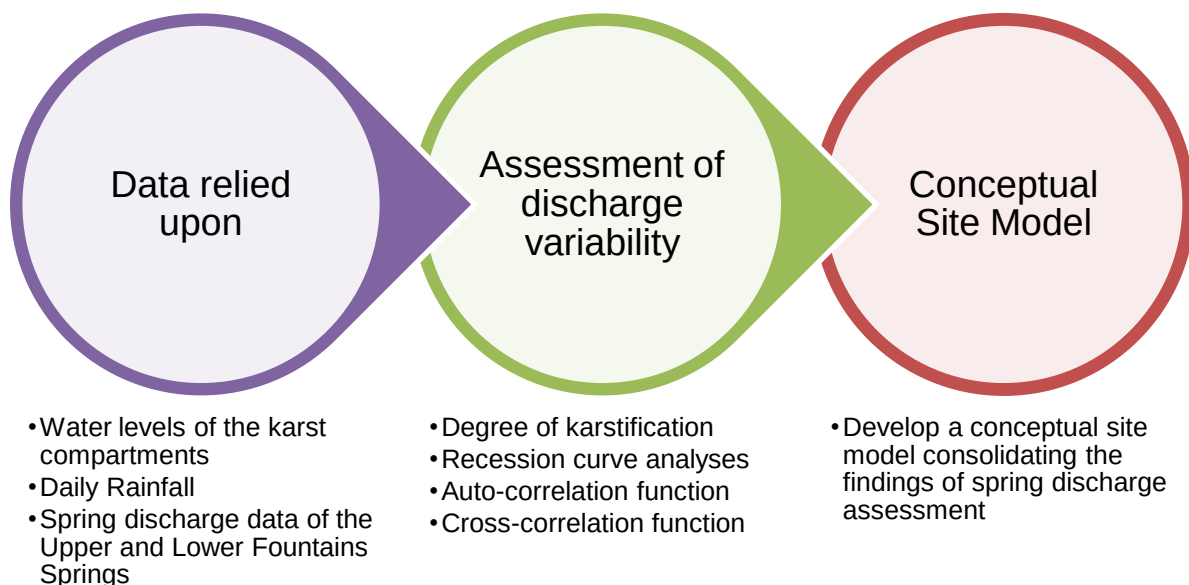


Figure 3-1: Process flow followed to assess groundwater flow mechanisms within the Fountain Karst Compartments

3.2 RAINFALL DATA

The dataset is assessed for accuracy and completeness where erroneous data is discarded (at least for spring discharge to ensure that the volumes are within acceptable ranges). The rainfall data received from the SAWS was collected from the nearest weather station (IRENE – WK) located in Irene, 12 km south of the study area.

The rainfall at the Irene weather station is measured from an electronic gauge called a “Tipping Bucket” rain gauge. The bucket includes a 203 mm diameter cylinder with a funnel-like opening, placed side by side on the ground to collect precipitation. The first bucket will

fill with precipitation during rainy events after which an amount equal to 0.2 mm decants into the nearest bucket which tips to send a signal to the weather station as indicated in Figure 3-2 (SAWS, 2022).

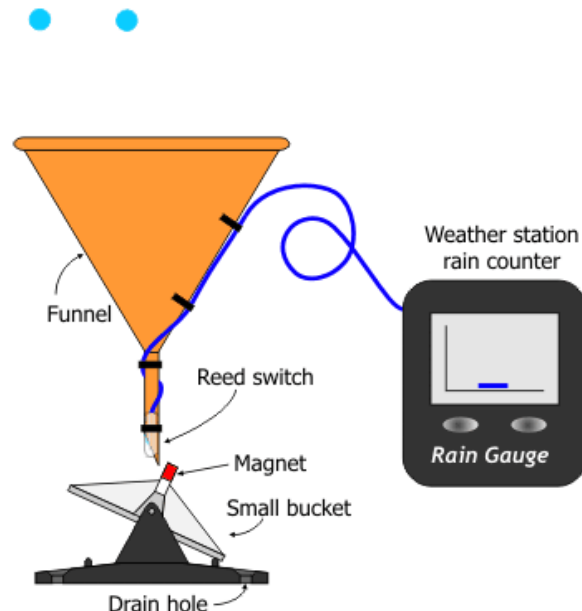


Figure 3-2: A Schematic of an electronic rain measuring gauge (KIFISA Meteo, 2022)

3.3 GROUNDWATER GAUGING DATA AND BOREHOLE LOGS

Borehole data retrieved from the DWS monitoring boreholes included continuous dataset from five groundwater monitoring boreholes in the Fountain East Karst Compartment (A2N0638, A2N0640, A2N0641, A2N0642 and A2N0685) and two groundwater monitoring boreholes in the Fountain West Karst Compartment (A2N0647 and A2N0757).

The monthly groundwater level dataset from the boreholes in the Fountain West Karst Compartment ranged from 1975 to 2020, and the groundwater level dataset from the Fountain East Karst Compartment ranged from 1984 to 2020. The groundwater levels are measured monthly using a water level meter similar to the meter shown as Figure 3-3.

The measurements of groundwater level are commonly recorded from a reference point such as casing level or ground levels. The groundwater level data received from the DWS was measured reference to the ground level, where survey elevations of the borehole casings referenced to the ground level were used to determine groundwater contours.



Figure 3-3: Picture showing groundwater level measurements from a monitoring borehole (Wallpaper Flare, 2022)

3.4 SPRING DISCHARGE DATA

The discharge dataset from the CoT, comprises of continuous spring discharge data recorded on hard copy field sheets received from July 2011 to September 2012 and February 2020 to April 2021. The dataset received from the CoT was not continuous for most years, mostly due to the digital meter not working because of power outages. An effort to select continuous yearly and monthly dataset to allow for interpretation of seasonal variability was made.

The interruption of measurements for springs is not uncommon as was also highlighted in the study conducted by Pavlic´ and Parlov (2019). The spring discharge from each spring is measured from the outlet/spring well using a water flow meter connected to a digital gauge where workers collect monthly readings. The digital meter does not digitally store data for retrieval should short-term measurements such as hourly readings be required (D. Tshabalala 2022, Personal communication).

The spring discharge is measured from a rectangular weir/plate, similar to the rectangular weir shown in Figure 3-4. The weir is installed at the outlet of each spring. Level loggers, stick gauges and ultrasonic sensors/eyes are installed in (logger and stick gauge) and over

(ultrasonic sensor/eye) the weirs to measure changes in the head/water column passing through the weirs.

The head of water in the weir, including the length of weir and time of each measurement are used to calculate the spring flows using the equation shown in Figure 3-4A. The spring discharge from the Upper and Lower Fountain Springs is recorded from electronic meters connected to a data logger which automatically calculates the spring flow from the data collected by the level logger and ultrasonic sensor (N. Schmulian 2023, Personal Communication).

The accuracy of the head/water column measured by the ultrasonic probe can be affected if the discharged water is highly turbulent or the weir is flooded (N. Schmulian 2023, Personal Communication). The ultrasonic sensor measures the time it takes for a transmitted pulse to be recorded at a receiver, which is used to monitor the changes in the water column within the rectangular weir (N Schmulian 2023, Personal Communication).

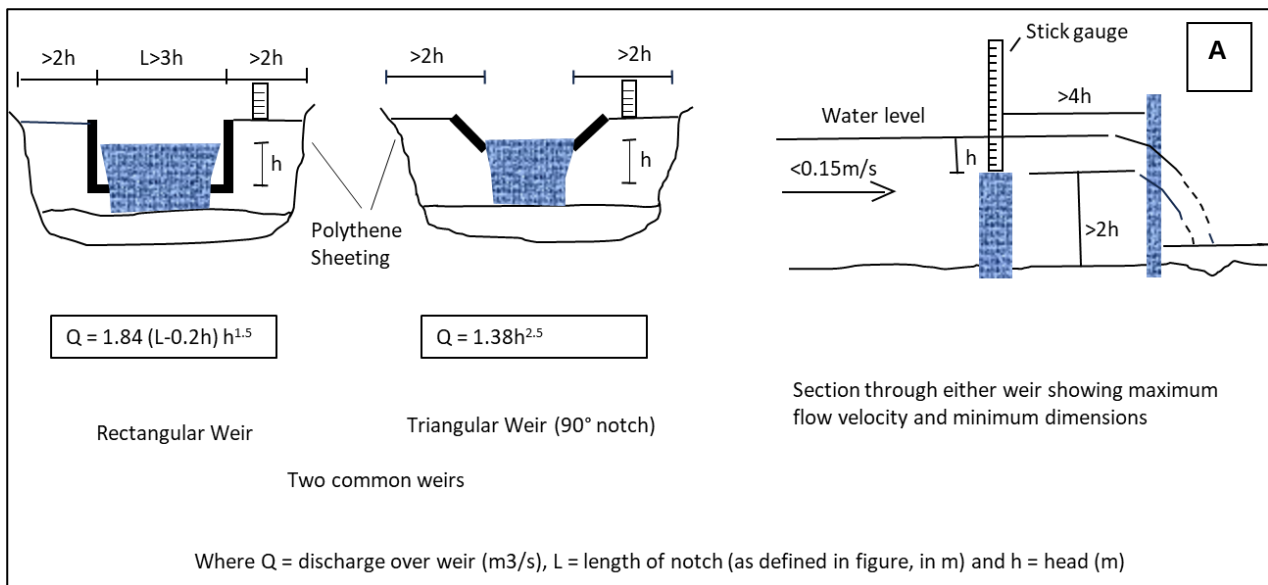


Figure 3-4: Example of a rectangular weir similar to the rectangular weir installed at the outlets of the Lower and Upper Fountain Springs (Modified from Loughborough University, 2023 and Emito, 2023)

3.5 DATA ANALYSES AND INTERPRETATION

This section describes methods used and followed to analyse the spring discharge, rainfall, and water level data. The methods selected for the assessment of hydrogeological conditions of Fountain Karst Compartments included spring hydrograph analyses, cross-correlation, and auto-correlation analyses.

3.5.1 ASSESSMENT OF DEGREE OF KARSTIFICATION

To assess the degree of karstification within the Fountain East and West Karst Compartments, the spring hydrographs, representing a single hydrological event is plotted. The properties of the spring hydrographs, including the maximum discharge rate, time at which the maximum discharge rate is attained, and the total time of the hydrological event are used to calculate the degree of karstification.

The calculated degrees of karstification are compared to degrees of karstification determined by Malik and Vojtková (2012) for other aquifers, to infer the likely flow regimes within the Fountain East and West Karst Compartments.

3.5.2 SPRING HYDROGRAPH ANALYSIS

The spring hydrographs from 2011 to 2012 and 2020 to 2021 events are plotted to identify the presence of recession curves (i.e. presence of rising and falling limbs over the monitoring period). The recession coefficient is calculated by fitting a line of best fit between the peak discharge and baseflow where the slope interpreted as a coefficient of recession is calculated using the peak flow as Y_1 and baseflow as Y_2 whilst X_2 is the time at peak flow and X_1 is time at which the line of best fit intersected discharge of baseflow. First, second and third order recession coefficients are calculated for hydrologic cycles with more than one recession curves to assess how flow changes over a hydrologic cycle.

The computational method of using the line of best fit follows a similar approach of computing recession coefficients using the exponential Maillet (1905) equation as presented in Section 2.5.1, which is considered the most applied method used to determine the recession coefficient. The recession coefficients are interpreted to infer the dominant flow regimes within the Fountain East and West Karst Compartments.

The computed recession coefficients and dominant flow regimes are useful in inferring the storage of groundwater within the Fountain East and West Karst Compartments, where recession flow is considered to represent higher storage with slow release whilst conduit flow is considered to represent higher storage with rapid release. Mixed flow is considered to present a combination of conduit and matrix flow with moderate groundwater release.

3.5.3 ASSESSMENT OF GROUNDWATER STORAGE

The methodology for assessing the recharge and storage of the Fountain East and West Karst Compartments was based on the computation of CCF and ACF described in subsections below.

3.5.3.1 CROSS-CORRELATION FUNCTION

The relationship between rainfall and spring discharge is assessed using the computation bi-variate cross-correlation correlograms. The cross-correlation correlograms assess the dependency of input and output variable over positive and negative lags of the time series, where a lag of 0 represent direct comparison of input and output data, whilst negative lags represent the relationship between the input variable at time before present time shifted at lags of $t - t_0$ to $t - t_x$ relative to the output variable (e.g., what happens to spring discharge before it rains), where x maximum lag and t is time in months.

A positive lag represents the relationship between the input variable at time after the present time shifted at lags of $t + t_0$ to $t + t_x$ relative to the output variable (e.g., what happens to spring discharge after it has rained).

A more positive cross correlation factor indicates higher correlation whilst a more negative cross correlation factor indicates no correlation. Temporal rainfall coinciding with available spring discharge data of 2011 to 2012 and 2020 to 2021 is selected as input data and considered to be an independent variable, whilst the spring discharge data is considered to respond to effects of recharge from precipitation and therefore selected as output of the functions.

Since spring discharge data received from the CoT is measured once or twice a month, it is deemed necessary to present the spring discharge as average monthly spring discharge to ensure compatibility with the rainfall data, also presented as average monthly rainfall data, before inputting the data into the Wessa Statistical Software (Wessa, 2022).

The average monthly rainfall is compared to monthly groundwater levels to assess the effect of rainfall on the response of rainfall. The model input parameters are not changed (i.e. left as default), except the following:

- Input or data x (average monthly rainfall used as input)
- Output or data y (average monthly spring discharge rates used as output)

A theoretical interpretation of the cross-correlation function is presented in Section 2.5.2. The results of the cross correlation correlograms are used to infer the recharge (i.e. autogenic or allogenic) of the Fountain East and West Karst Compartments.

3.5.3.2 AUTO CORRELATION FUNCTION

The univariate auto correlation function is computed to assess the linear dependency of a time series against a positively lagged version of the time series. The auto-correlation

function is used to identify the presence of linear dependency between values in a time series (i.e. if higher spring discharge is observed today, will a higher spring discharge be observed the following day).

The results of auto-correlation function are important in understanding the storage capacity of karst aquifers where a more positive auto-correlation function indicates a strong linear dependency between the variables of the original time series and a lagged version of the time series, and a negative auto-correlation function indicates non-linear dependency between the time series and a lagged version of the time.

The higher the linear dependency, the higher the storage capacity of the aquifer and vice-versa. An auto-correlogram with a sharp slope is inferred to indicate a hydrogeological system with low memory effect whilst a gentle slope indicates a system with a higher memory effect and thus higher groundwater storage.

The Wessa Statistical Software (Wessa, 2022) was also used to compute auto-correlation correlograms, where model input parameters were left as default except the input data (used separate dataset of spring discharge from the Upper and Lower Fountain including separate water level data measured in boreholes from the Fountain East and West Karst Compartments).

3.5.4 BOREHOLE DENSITY ASSESSMENT

A query of the WARMS databases will be conducted to assess the distribution of registered boreholes drilled into the Upper and Lower Fountain Karst Aquifers and a map showing the locations of WARMS registered boreholes and distribution of borehole yields will be produced. The results of the WARMS database query will provide insight on the presence of new groundwater abstractions which could be affecting spring discharge within the study area.

3.5.5 SPRING DISCHARGE DATA AND CHANGES IN LAND USE

Aerial imagery from 2010 to 2021 will be assessed for the presence of land use changes which could potentially alter the flow groundwater within the Fountain East and West Karst Compartments. A comparison of significant changes in land use with periods of significant change in spring discharge will be conducted to assess whether land use could have affected spring discharge.

3.5.6 DEVELOPMENT OF A REFINED CONCEPTUAL MODEL

The development of the conceptual model followed the procedure developed by Izady et al. (2014) as shown in Figure 3-5. The data collected, as required in Step 0 of the procedure, includes rainfall data, spring discharge data, groundwater level data, lithology data, storativity and hydraulic conductivity. The controlling observations as required in Step 2, will include rainfall, groundwater level and spring discharge data.

A digital elevation model of the study area incorporating information from statistical assessment of lithology and positions of the dyke indicated on the model from Naidoo (2014), including the latest average water levels will be prepared as part of Step 2.

The aquifer physical boundary will be as delineated in literature, whilst the boundary conditions will consider the area around the north-south syenite dyke and Irene dyke as a no flow boundaries, and areas along the Apies River as a head dependent flow boundary as well as the remaining areas as constant head flow boundary. The initial model was assessed for any inconsistencies through an inconsistency assessment (CE).

The hydrodynamic properties of the aquifer as required in Step 3 will be based on information available in literature and presented in the study by Naidoo (2014). The information will further incorporate the results of the spring recession curves (depicting dominant flow regime with each compartment), auto-correlation (showing storage capacity of each compartment) and cross-correlation functions (indicating the type of recharge within each compartment and relationship between recharge and spring outflow). A CE will be conducted to assess the data used to determine the hydrodynamic properties and adjusted as required before proceeding to Step 4.

The spring discharge data will be used to present discharge of the spring as required in Step 4, and information on recharge will be sourced from isotope assessment conducted by Naidoo (2014).

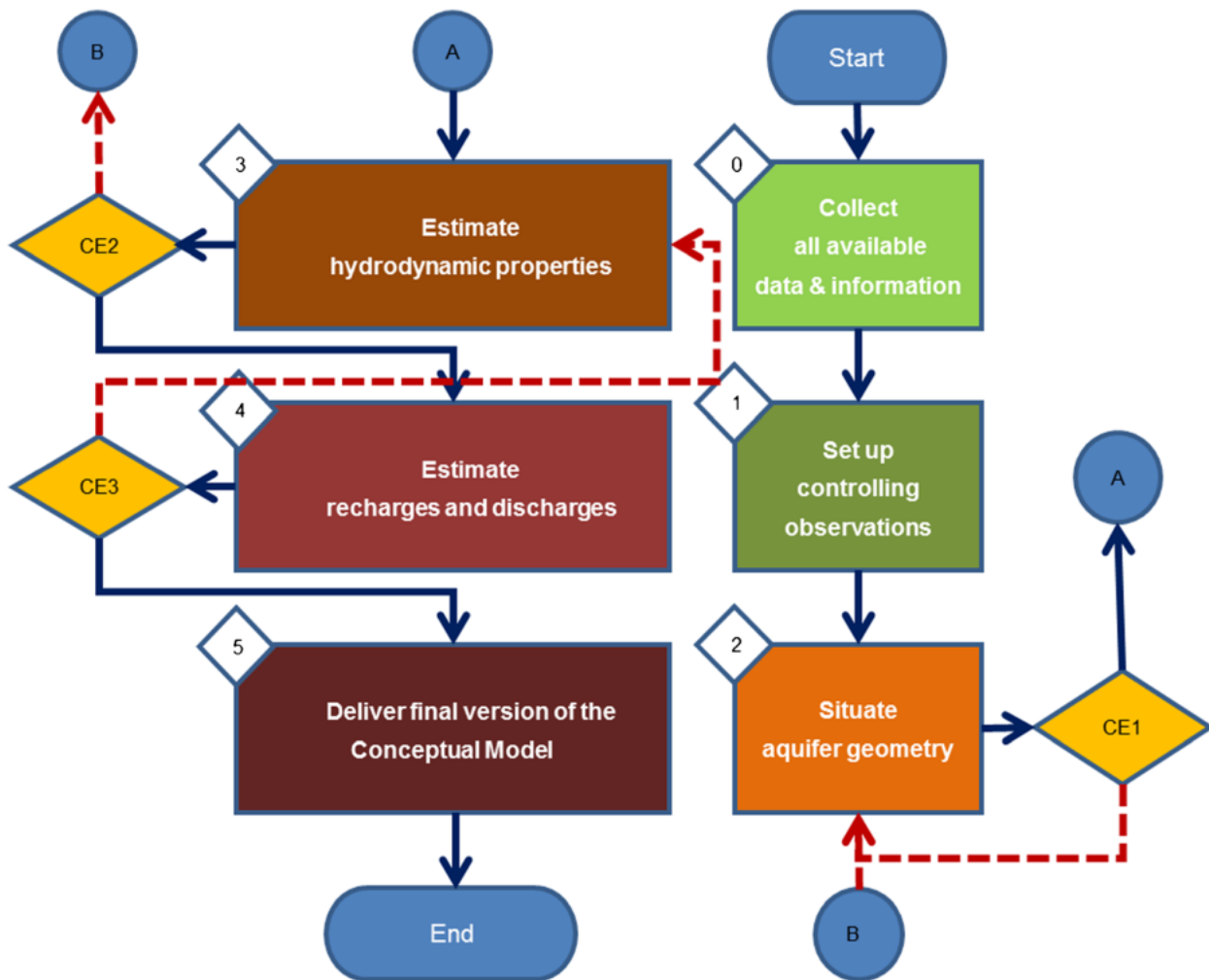


Figure 3-5: Process flow diagram of developing a hydrogeological conceptual model (From Izady et al., 2014)

4

DESCRIPTION OF THE STUDY AREA

4.1 PHYSIOGRAPHY AND SURFACE DRAINAGE

The study area defined by the Fountain East and West Compartments as shown In Figure 4-1, falls within the jurisdiction of the City of Tshwane Metropolitan Municipality in Gauteng Province, South Africa. The Fountain springs form part of the Crocodile and Marico Water Management Area (MWA), part of the Greater Limpopo Water Management Area (WMA 1).

The WMA 1 encompasses quaternary catchment A23D with a gross catchment area of 145 km² and forms part of the Crocodile Basin as shown in Figure 4-1 (Naidoo, 2014; Water Research Commission, 2012; Bigcon Consortium, 2010; DWS, 2006a). Vegter (1986), suggested that the exploitable storage of the Fountain East Karst Compartment is 4.5 to 7.5 Mm³, whilst the exploitable storage of the Fountain West Karst Compartment is 14 to 23 Mm³.

According to Hobbs (2004), the Fountain West Compartments including the East and West Doornkloof Compartments found south of the Fountain Compartment, form a single groundwater management unit (GMU), called GMU 2b, whilst the Fountain East Karst Compartment forms a separated groundwater management unit called GMU 2f. A groundwater management unit is inferred based on similar surface drainage and boreholes with hydraulic connectivity.

The major rivers within the A23D quaternary catchment are the Crocodile River receiving 75% of the run-off from the A23D quaternary catchment the Olifants and Marico Rivers receiving 25 - 20% of run-off from the A23D quaternary catchment (Naidoo, 2014). The tertiary catchments considered to contribute to recharge at the study area through surface drainage/run-off include the Apies-Pienaars: Roodeplat (A23A), upper Crocodile: Hartebeespoort (A21B to A21H) and Apies-Pienaars: Upstream of Klipvoor (A23D and A23E) (Naaido, 2014).

The Apies River flows from south to north along the study area whilst the south-westerly flowing Hennops River is located west of the study area. The Apies and Hennops Rivers receive baseflow from the karst aquifers (Meyer, 2014). Two dams located at Monument Park near Waterkloof Boulevard and Erasmus Park and within a 6 km radius of the site were identified as major surface water sources near the study area. The major surface water body within the catchment is the Rietvlei Dam located 11 km southeast of the study area.

According to Chief Directorate: Surveys and Mapping, Topographic map sheet 2528CC, dated 2005 and scaled at 1: 50 000, the southern portion of the study area is situated at an elevation of 1 480 meters above mean sea level (mamsl) whilst the northern portion of the study area is at an elevation of 1 420 mamsl.

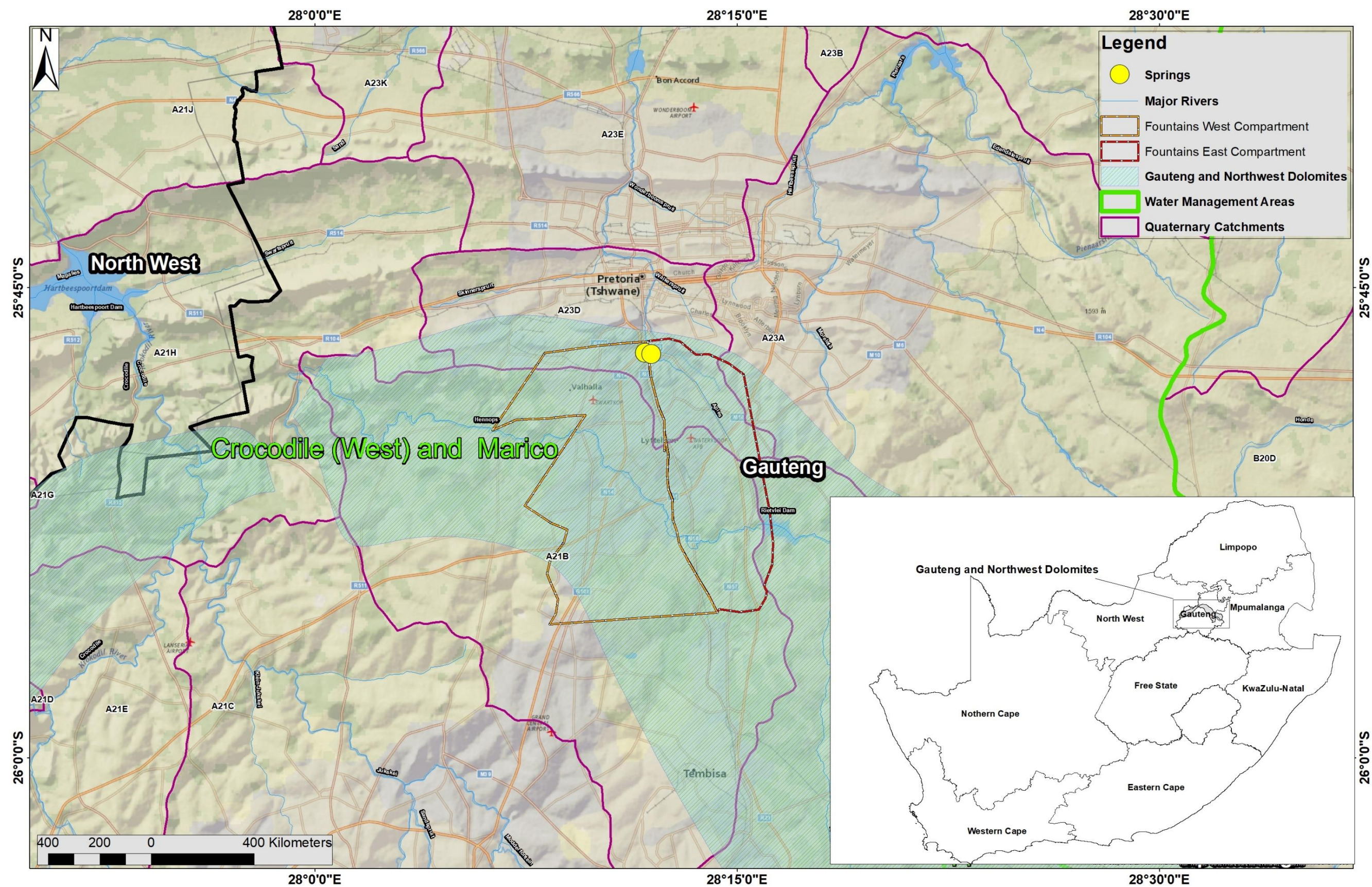


Figure 4-1: Map showing the Crocodile West and Marico water management area, the parts of the Gauteng and Northwest Dolomites, including the A23D hosting the Fountain East and West Karst Compartments Groundwater Management Units (GMUs) and major rivers within the A23D quaternary catchment and nearby catchments (Map produced using ArcGIS, 2022)

The karst morphology of the Pretoria area has been described as an escarpment type morphology with rugged topography (Meyer, 2014). The clastic sedimentary rocks of the Transvaal Supergroup form east-west trending ridges along the northern boundary of the A23D catchment.

The elevation of the ridges varies from ~1 370 mamsl to ~1 380 mamsl. The southern portion of the catchment comprises of low relief and undulating plains on dolomites formation with elevations varying from ~1 230 mamsl to ~1 350 mamsl. Locally the topography of the study area gently falls from ~1 480 mamsl along the southern portion in Irene and surrounding areas to ~1 389 mamsl at the study area, indicating general drainage of surface water towards the north, towards the Limpopo River (Meyer, 2014).

4.2 RAINFALL AND TEMPERATURE

The A23D catchment receives rainfall of 706 mm/annum and experiences evaporation of 1 769 mm/annum, whilst run-off accounts for 10.45 million cubic meters (MCM) (Naidoo, 2014; Water Research Commission, 2012). The readily available rainfall data from the Irene weather station (station number 05133822), located at the SAWS office in Irene (geographic coordinates 25°54'37.80"S and 28°12'38.16"E), deemed to be closer to the study area is shown in Figure 4-2. The rainfall data plotted in Figure 4-2 indicates higher monthly rainfall events in 2016 (113 mm), 2018 (122 mm) and 2019 (103 mm).

The cumulative annual rainfall for 2011 to 2020 presented in Figure 4-2 were computed to assess changes in rainfall patterns for those years when spring discharge data collected for this study was available. The computed cumulative rainfall data indicates higher cumulative rainfall in 2014 (977 mm), 2011 (854 mm) and 2017 (825 mm), whilst the lowest cumulative rainfall was experienced in 2015 (417 mm), 2018 (551 mm) and 2013 (593 mm).

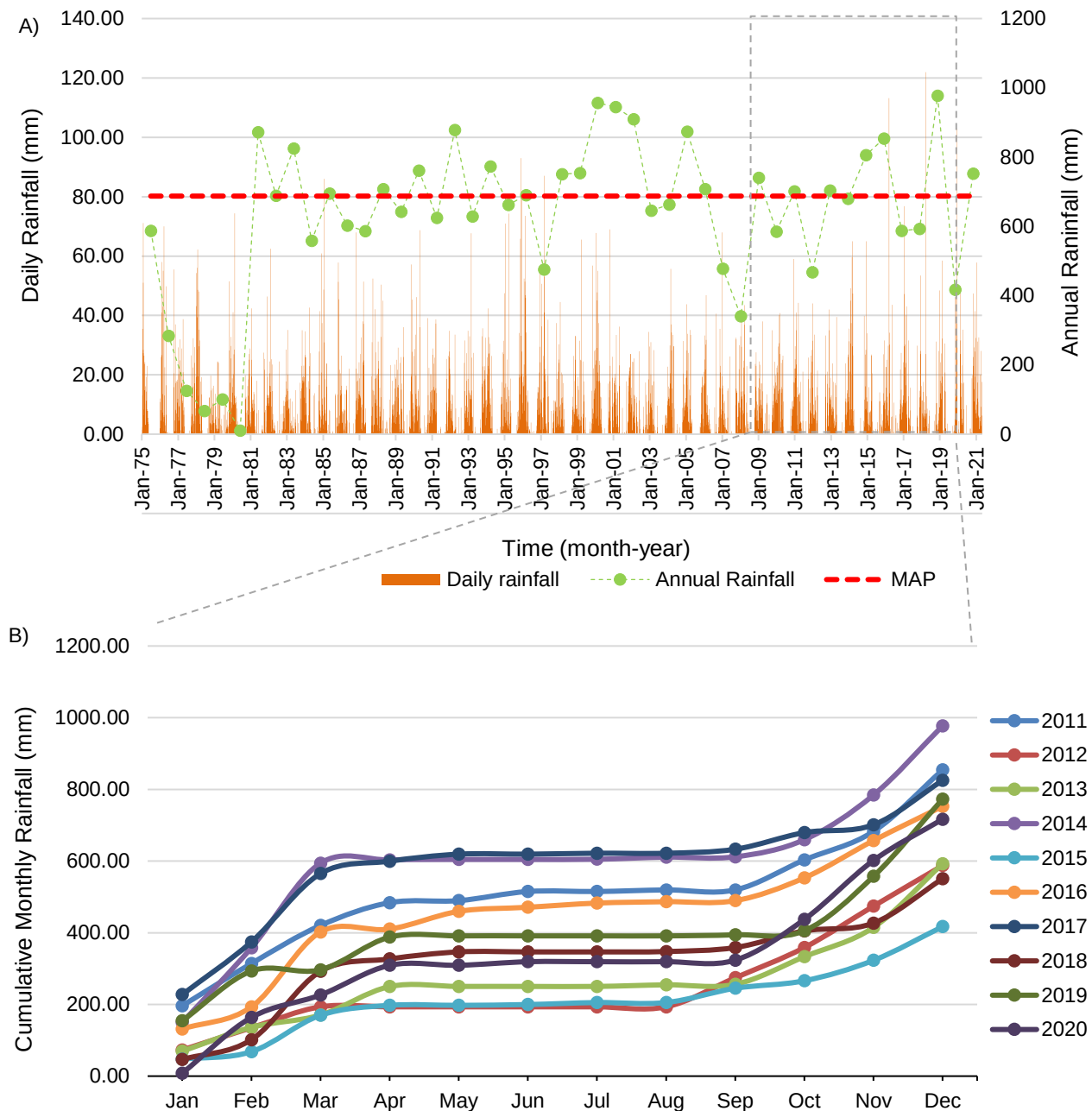


Figure 4-2: Time series of precipitation (A) from January 1975 to April 2021, and cumulative monthly rainfall for periods of between 2011 to 2020. Data collected from a meteorological station in Irene, Pretoria (South African Weather Services, 2021)

The wet season is experienced from September until April (8 months) with the highest average rainfall (97 mm) experienced towards the end of January where maximum rainfall can reach ~190 mm as shown in Figure 4-3. The dry season is experienced for 3 months (in June to August), where the average rainfall is 2 mm as shown in Figure 4-3 (Weather Spark, 2022).

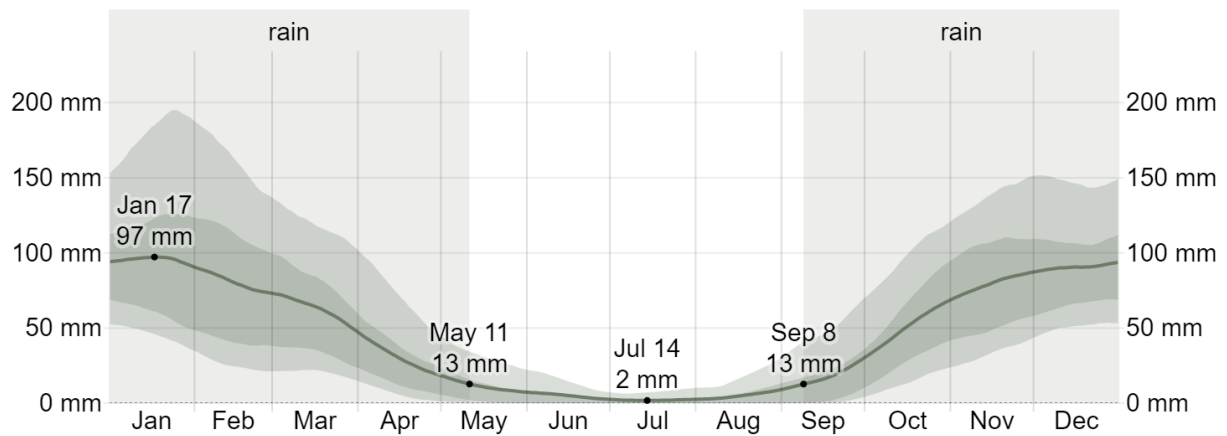


Figure 4-3: Average rainfall of Pretoria, measured between 2014 and 2022 indicating the rainy season (Weather Spark, 2022)

Pretoria has long summers and a shorter dry winter period. The highest temperatures are encountered between September to March and range between 26°C to 28°C during the rainy season as shown in Figure 4-4 and Figure 4-3. The winter season is experienced between late May to late July where temperatures range between 8°C in May, 5°C in June to 7°C in July as shown in Figure 4-4 (Weather Spark, 2022).

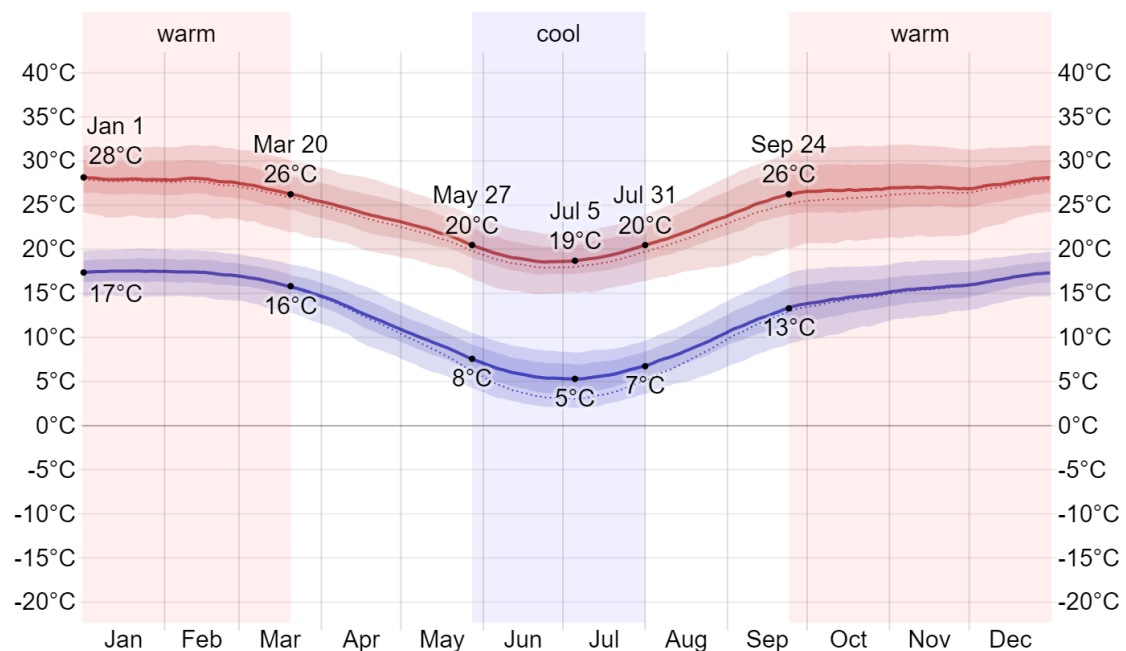


Figure 4-4: Average monthly temperature of Pretoria, measured between 2014 and 2022 (Weather Spark, 2022)

4.3 LAND COVER AND LAND USE

The land use of the Pretoria area, including the study area (Fountain East and West Karst Compartments) is shown in Figure 4-5. The land use within the study area (Fountain East and West Karst Compartments) comprises of recreational areas, whilst surrounding areas

comprise of residential, commercial, and recreational areas. The Upper and Lower Fountain springs are located within the Groenkloof Nature Reserve.

The land cover of the study area comprises of a mixture of indigenous forests and dense bush as would be expected for a nature reserve, including a water course defined as a wetland which is the Apies River as indicated in Figure 4-5 (SANBI, 2022). The dominant land use at the study area comprises of urban residential and commercial land uses (yellow shaded areas), bare built-up areas (purple shaded areas) and mixture of urban sports facilities and golf courses (light green shaded areas).

The site is located near the Metrorail line located 100 m west whilst the Gautrain rail line is located 500 m west of the site as shown in Figure 4-6. The study area is accessed through the N14 and M18. The Lyttelton dolomite mine is located 6 km south, and up-hydraulic gradient of the study area.

Google Earth Imagery® of surface features where higher groundwater recharge or discharge would be expected is shown in Figure 4-6. The features as observed from 2021 Google Earth Imagery® includes a man-made dam near Monument Park, located approximately 5 km southeast of the study area, Services golf course located 3.5 km west, Waterkloof golf course located 1.5 km east, Waterkloof airbase located 3.5 km south, Erasmus Park dam located 5 km southeast, Lyttelton dolomite mine located 6 km south, Rietvlei dam located 11.5 km south-southeast, and the Gautrain rail loop located 0.3 km west. The dominant surface water features expected to exacerbate surface recharge are golf courses and dams.

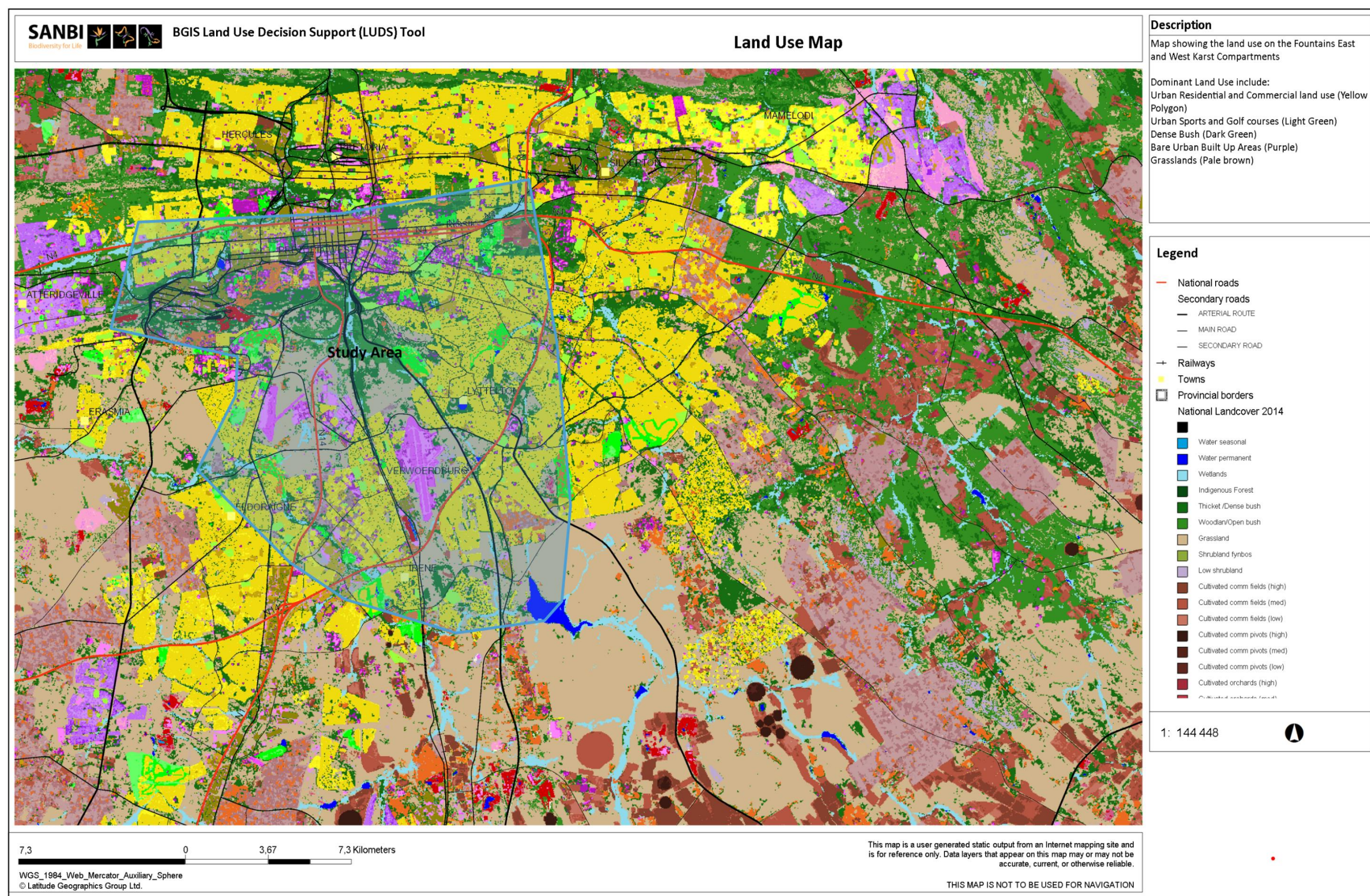


Figure 4-5: Land Use Map from the SANBI Website showing the dominant land uses within the study area defined by the Fountain East and West Karst Compartments, comprising of urban residential and commercial land use, and dense bush of the Groenkloof Nature Reserve (SANBI, 2022)

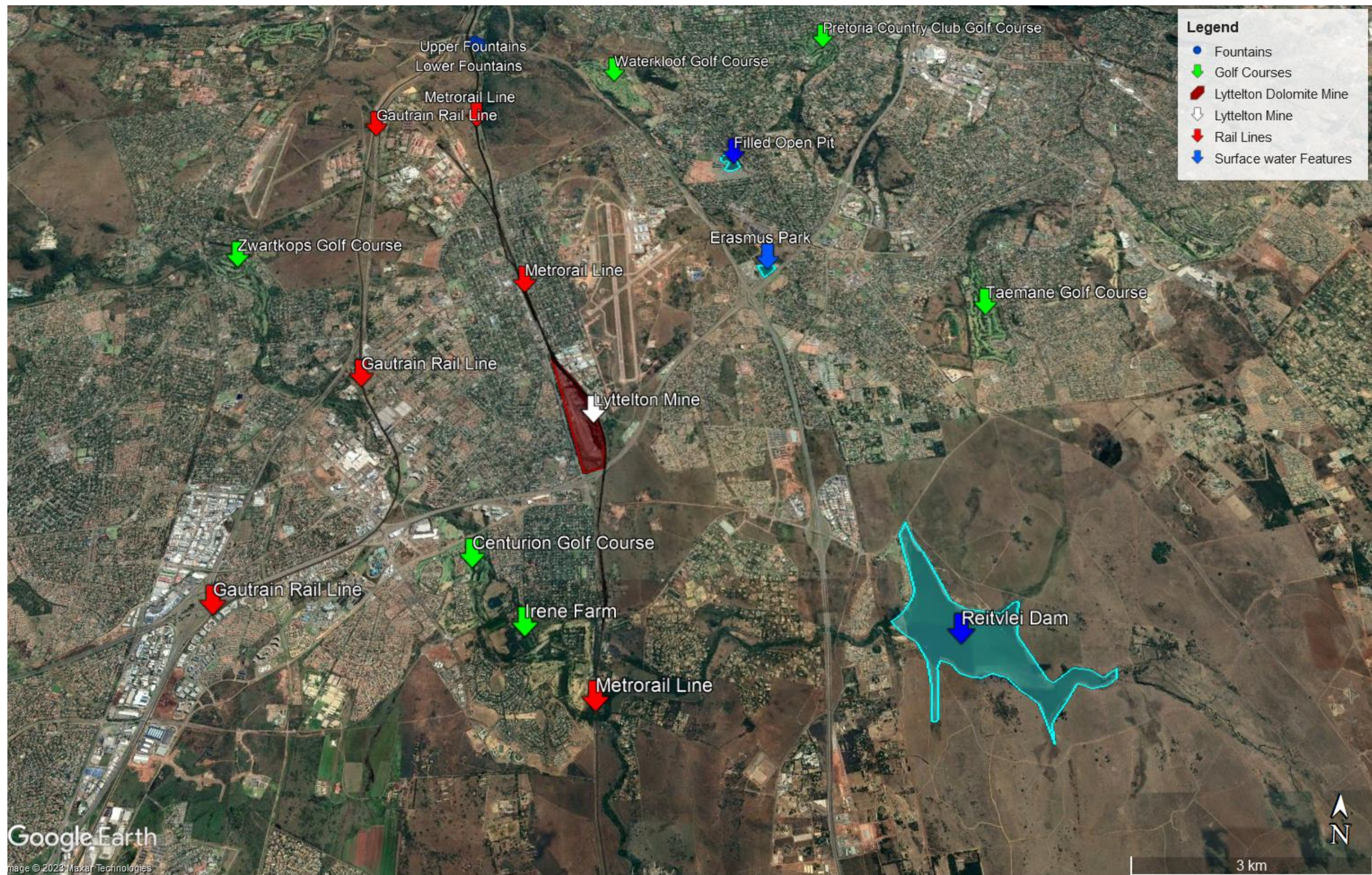


Figure 4-6: Google Earth Imagery® showing locations of surface water features and mines where higher recharge and dewatering is expected, locations of the Gautrain and Metrorail lines, golf courses and farms where intense water use and recharge is expected.

4.4 REGIONAL AND LOCAL GEOLOGY

The local geology of the study areas has extensively been described by various authors including Naidoo (2014) and Meyer (2014). According to the Department of Mineral and Energy Affairs, Map Sheet 2528, Pretoria, scaled at 1:250 000 and dated 1978 as shown in Figure 4-7, the geology of the study area comprises of dolomites of the Malmani Subgroup forming part of the Chuinespoort Group of the Transvaal Supergroup.

The dolomites occur with chert layers used as markers for different formations of the Malmani dolomites. The pre-Karoo (1.45 – 1.2 Ga) syenite dykes have intruded the dolomites of the Malmani Subgroup and resulted in compartmentalisation of the dolomite aquifer system of the study area into the Fountain West and East Karst Compartment aquifers.

In addition to the syenite dyke which has compartmentalised the Fountain Karst Aquifer, the hydrostratigraphy making the Fountain Karst Aquifer comprises of multiple sills and faults of similar age as the syenite dyke (Naidoo, 2014). The general trends of dykes are N-S and E-W whilst the faults are trending NE-SW, NNW-SSE and NNE-SSW (Holland, 2007). The dykes, sills and faults have been described as important in controlling the flow of groundwater within the compartments (DWS, 2006a).

Minor outcrops of the Eccia Group of the Karoo Supergroup comprising of shale, shaly sandstone, grit, sandstone, and conglomerate are found along the eastern portion of the study area whilst, the quartzite of the Timeball Hill Formation of the Pretoria Group forming part of the Transvaal Supergroup, make up the westerly to easterly trending ridge found towards the northern portion of the study area as shown in Figure 4-7.

The 2 000 m thick Malmani dolomites have been divided into five formations as indicated in Table 4.1. The distinctive feature differentiating the dolomite formations are the chert-rich layers thought to have been deposited in subtidal environments (Meyer, 2014). The Black Reef Formation comprising of quartzite and conglomerate underlie the Malmani Subgroup whilst, the clastic sedimentary rocks of the Pretoria Group overlie the Malmani dolomites.

The Monte Christo Formation comprising of alternating layers of chert-rich and poor dolomites are found at the study area (Meyer, 2014). The chert-rich dolomites of the Upper Monte Christo Formation form ridges due to a higher resistance to erosion whilst, low relief areas are found on more weatherable chert-poor Middle and Lower Monte Christo

Formations (Meyer, 2014). A summary of the geology and thickness of the stratigraphic units at the study area is presented in Table 4.1.

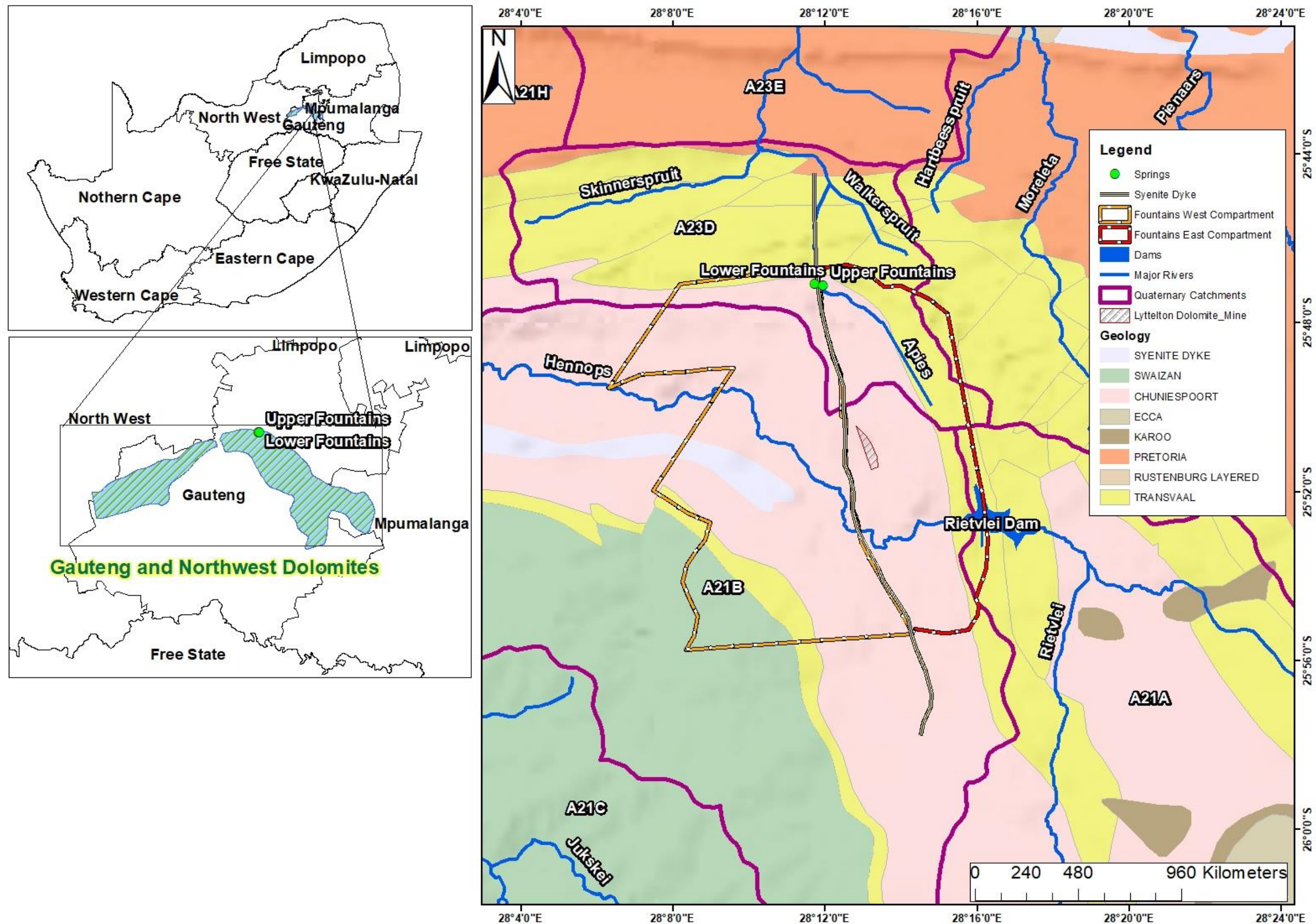


Figure 4-7: Map showing the distribution dolomites within quaternary catchment A23D, hosting the Fountain East and West Karst Compartments associated with the Lower and Upper Fountain Springs. The locations of major rivers and dams including the Apies River fed by the springs is shown on the map

Table 4.1: Stratigraphic unit of the study area (Modified from DWS, 2006a and Cobbing, 2017)

Supergroup	Group	Subgroup	Formation	Geological Age of Deposition ¹	Approximate thickness ^{1,2,3,4}	Description
Post Karoo soil				<65 Ma	~ 10 – 40 m	Sandy silt and clayey silt
Karoo	Ecca	Dwyka		190 – 280 Ma	~ 10 – 60 m	Sandstone, mudstone
		Vryheid			<500 m	Shale and mudrock
Post Transvaal/ Pilanesberg age volcanic intrusion			Syenite Dyke	1 200 – 1 450 Ma	~60 m	Pyroclastic and lava flow deposits
Transvaal	Pretoria	Lower Pretoria	Timeball Hill	2 100 – 2 300 Ma	~ 1 100 m	Shale and subordinate sandstone
			Hekpoort			Volcanic rocks
	Chuinespoort	Malmani	Frisco		~400 m	Chert-free dolomite
			Eccles		~ 380 m	Fe-Mn rich dolomite, rich in chert which become enriched towards the top of the formation and has stromatolite and oolitic bands
			Lyttelton		~ 150 m	Fe-Mn rich, chert depleted and has well developed stromatolite mounds
			Upper Monte Christo		~ 258 m	Dolomite rich in chert
			Middle Monte Christo		~ 162 m	Dolomite poor in chert
			Lower Monte Christo		~ 275 m	Dolomite poor in chert
			Oaktree		~ 200 m	Interlayered carbon rich shale with depleted chert
	Black Reef		~ 30 m		Conglomerate and quartzite with interlayered with carbonaceous shale	
Ventersdorp Supergroup				2050 – 2700 Ma	> 3 978	Andesite, quartz porphyry, conglomerate, calcareous shale, quartzite, and lava
Crystalline Basement Complex				>3090 Ma		Granite gneiss

¹ Wilkins, Eriksson, and van Schalkwyk. 1987. Two generations of Karst-fill sedimentary rocks within Chuinespoort Group dolomites south of Pretoria. South African Journal of Geology, 90(2), pp: 155-67

² DWS. 2006a. A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa. Volume 2

³ Catuneanu and Eriksson. 2000. Sequence stratigraphy of the Precambrian Rooihooigte – Timeball Hill rift succession, Transvaal Basin, South Africa. *Sedimentary Geology*, 14(1-2), pp. 71-88

⁴ Department of Water and Sanitation. 2006b. Vaal River System: Large Bulk Water Supply Reconciliation - Strategy Groundwater Assessment: Dolomite Aquifers. DWAF Report Number: P RSA C000/00/4406/06

4.5 HYDROGEOLOGICAL SETTING

Vegter (1995) highlighted the importance of the north-south striking syenite dyke of the Pilanesberg age in compartmentalising the Fountain karst aquifer into the Fountain West and East Karst Compartments as shown in Figure 4-8.

The identification of the Fountain Karst Compartments was observed from magnetic data of an aeromagnetic survey (Holland and Wiegman, 2009). The varying groundwater levels of the Fountain Karst Compartments was identified as another distinguishing feature of the aquifers (Naidoo, 2014). The west-east trending Irene dyke crosscuts the north-south dyke that has compartmentalised the Fountain karst aquifers as shown in Figure 4-8.

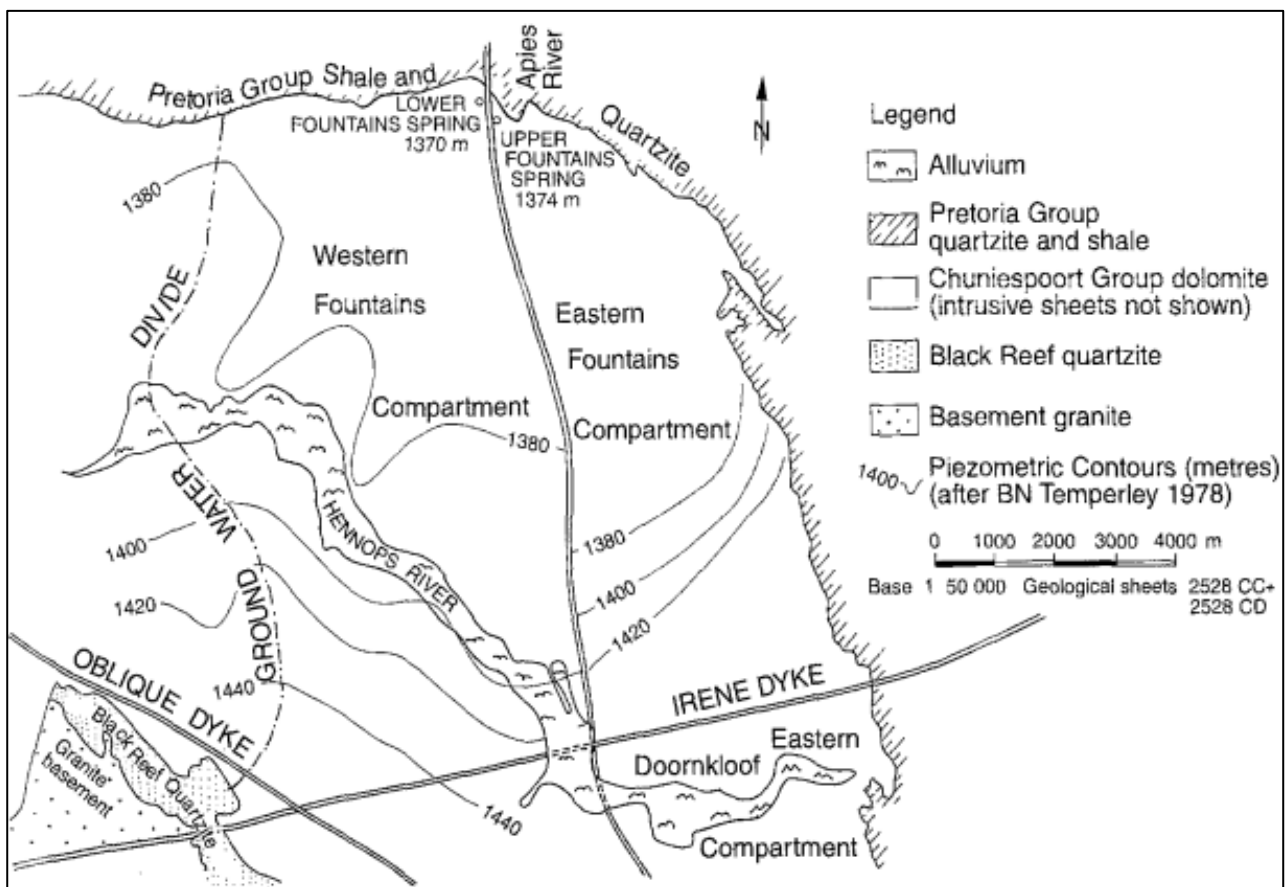


Figure 4-8: Map showing locations of the Upper and Lower Fountain Springs include the syenite dyke which compartmentalised the dykes (Vegter, 1995)

The Fountain West karst aquifer feeds the Lower Fountain Spring (shown in Figure 4-9) whilst the Fountain East Karst aquifer feeds the Upper Fountain Spring. The Lower Fountain Spring is located at an elevation of 1 370 mamsl whilst, the Upper Fountain Spring is located

4 m higher at an elevation of 1 374 mamsl. The Upper and Lower Fountain Springs are situated 800 m apart at the Groenkloof Nature Reserve (Dippenaar, 2013).

The Hennops River flows from the Doornkloof East Karst Compartment from east to northwest over the Fountain West Karst Compartment. The groundwater flow contours generated indicate general groundwater flow towards north as shown in Figure 4-8, including a groundwater divide inferred west of the Fountain Karst Compartment (Vegter, 1995).



Figure 4-9: Photograph of the Lower Fountain Spring Outlet into the Apies River

The presence of chert within the Upper Monte Christo, Lower Monte Christo and Eccles has resulted in the development of groundwater reservoirs. The reservoirs were developed due to higher processes of chemical weathering within the dolomite and less weathering of the surrounding chert layers, forming skeletal layers (Foster, 1998). Nonetheless, the inherent presence of dissolution fractures within karst aquifers results in higher storage (if well developed) and transmissivity when well interconnected (Trollip, 2006). A summary of hydrogeological properties of karst aquifers are presented in Table 4.2.

Table 4.2: Estimated hydrogeological parameters of karst aquifers in South Africa (Naidoo, 2014)

Effective Porosity	Transmissivity	Storage	Storativity	Storage coefficient	Reference
2 – 14%	10 – 30 000 m ² /day	0.0005 – 9.5%	-	-	Buttrick <i>et al.</i> (1993)
1 – 3.4%	10 – 30 000 m ² /day	-	-	-	Foster (1989)
20%	10 – 30 000 m ² /day	12 000 Mm ³	0.0001 – 0.1	-	Mulder (1988)
-	-	5 000 Mm ³	-	-	DWAF (2006a)
-	-	-	-	0.1	DWAF and WRC (1995)

Notes:

-: Not reported

Mm³: Million cubic meters

The water discharged from the Lower and Upper Fountain Springs, flows into the collection chamber (shown in Figure 4-10) for treatment and is transferred to the Findlay Reservoir, where excess water (~10 Ml/day) is transferred to the pump house (as shown in Figure 4-12) for further transfer, through gravity to the Salvokop Reservoir. The dimensions of the rectangular weir installed at the outlet of the Upper Fountain Spring is slightly bigger than the dimensions of the rectangular weir installed at the outlet of the Lower Fountain Spring and could result in higher spring discharges measured at outlet of the Lower Fountain Spring (N. Schmulian 2023, Personal Communication).



Figure 4-10: Photographs of the collection chamber and pump house receiving water from the Lower and Upper Fountain Springs

4.6 GROUNDWATER RECHARGE

The groundwater recharge of the Gauteng dolomites within which the Fountain East and West Karst Compartments fall, was estimated to be between 7% to 15% of the mean annual precipitation (Meyer, 2010). The study by Meyer (2010) further indicated that land use can affect the estimated recharge of the Gauteng dolomites, where areas with impervious surfaces will have limited recharge compared to areas with more pervious surfaces and presence of leaking pipes.

The levels of stable isotopes of hydrogen and oxygen (deuterium (δH^2) and Oxygen-18 (δO^{18})) in rainfall from weather stations in Brooklyn, Council for Scientific and Industrial Research (CSIR), Forum, Lynwood Road and Menlo Park were compared to δH^2 and δO^{18}

values water samples collected from the Lower and Fountain Springs as shown in Figure 4-11.

The assessment of δH^2 and δO^{18} isotopes of samples from the Lower and Upper Fountain Spring conducted by Naidoo (2014), indicated a slightly higher evaporative (i.e., a higher degree of fractionation) signature when compared to δH^2 and δO^{18} of rainfall from Pretoria, as shown by an isotopic signature slightly below the local meteoric line (LMWL), suggesting that the recharge area of the Fountain East and West Karst Compartments is not in the Pretoria area or the residence time of recharge within the vadose zone prior to reaching the water table is prolonged (Naidoo, 2014).

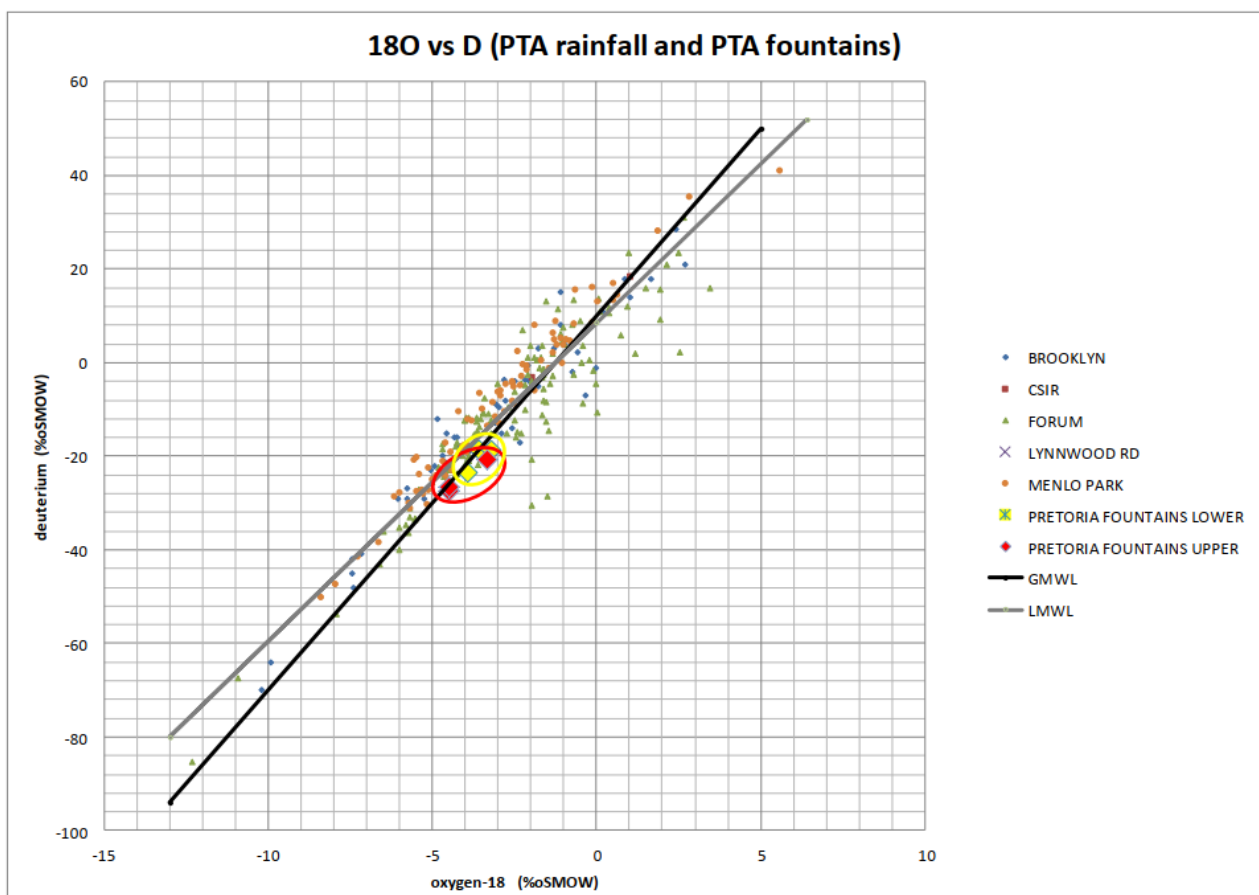


Figure 4-11: Plot of deuterium (δH^2) and Oxygen 18 (δO^{18}) of rainfall from stations in Brooklyn, CSIR, Forum, Lynwood Road and Menlo Park compared to δO^{18} and δO^{18} of groundwater from the Lower and Upper Fountain Springs, and the local meteoric lines (Naidoo, 2014)

4.7 GEOLOGICAL CONCEPTUAL MODEL

The geological conceptual model of the Fountain East and West Karst Compartments is shown in Figure 4-12. Naidoo (2014) completed a statistical analysis of the lithology of the

DWS boreholes drilled into the Fountain East and West Karst Compartments to infer representative lithology for producing a geological conceptual model shown as Figure 4-12. The analyses indicated the presence of soil at depths of between 0 to 4.78 m below ground level (mbgl), overlying chert from 11.21 m to 32.38 mbgl, on dolomite occurring at depths of between 17.29 m to 38.66 mbgl with a maximum depth of 103 mbgl.

The overlying soil cover is comprised of weathered dolomite and chert/wadi including clayey sand in where the syenite dyke was weathered (Naidoo, 2014). Two major faults trending northwest-southeast, including the north northeast-south southwest trending syenite dyke considered are indicated on the geological conceptual model shown in Figure 4-12. The two faults are considered major groundwater flow areas whilst the syenite dyke is considered a no-flow zone differentiating the two compartments.

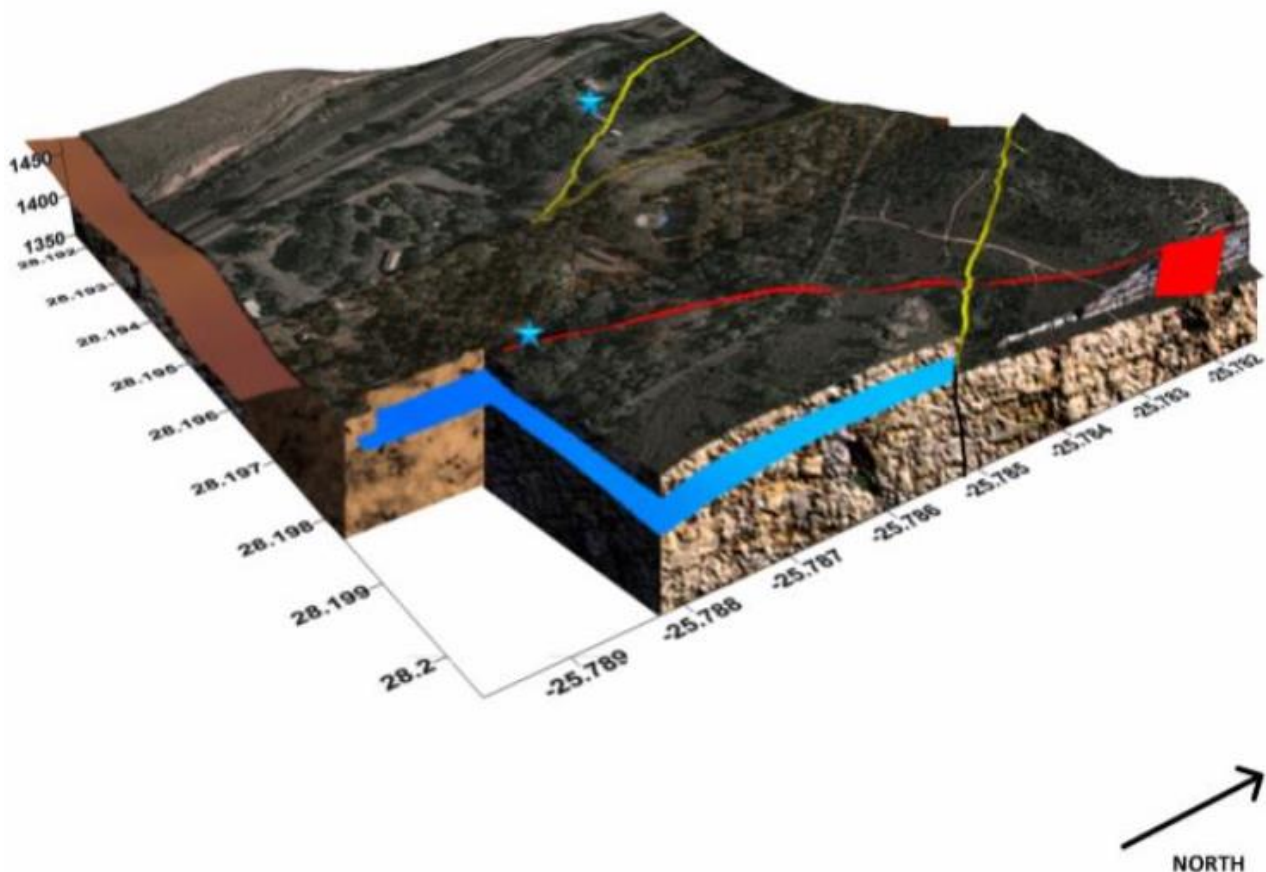


Figure 4-12: Conceptual model of the Fountain East and West Karst Compartments showing the locations of the Lower and Upper Fountain Springs including dominant geological structures such as faults as yellow lineaments and the syenite dyke as a red lineament (Naidoo, 2014)

4.8 GROUNDWATER LEVELS AND FLOW DIRECTION

The locations of DWS monitoring boreholes within Fountain East and West Karst Compartments are shown in Figure 4-13. The groundwater levels of a selection of boreholes representative of the Fountain East and West Karst Compartments were plotted on graphs shown as Figure 4-14 and Figure 4-15.

The resolution of the temporal groundwater levels was further increased by focussing on monitoring events that occurred between 2011 to 2020 as shown in Figure 4-14 and Figure 4-15, to allow for further comparison with the available spring discharge data of the Lower and Upper Fountain Springs.

The groundwater levels from the DWS monitoring borehole had four readings (January, October, November, and December) in 2020 which were reportedly limited by cost cutting measures and the Corona Virus Diseases (COVID) resulting in travel restrictions nationwide.

The groundwater within the Fountain West Karst Compartment was shallower between 1976 and 1981 and ranged between 1442.88 and 1391.75 mamsl in monitoring borehole A2N0757. The shallower water levels could indicate limited hydraulic connectivity between the shallow and deeper aquifers at the time, or less to no groundwater abstraction at the time. A period of no monitoring is observed for groundwater levels in A2N0757 between 1981 to 2002.

The groundwater elevations from 2003 and 2020 were less erratic and ranged between 1395 to 1375 mamsl, indicating a significant drop of approximately 20 m in the water table when compared to water elevations of between 1442.88 mamsl and 1435.37 mamsl, measured in A2N0757 as indicated in Figure 4-14. The deeper groundwater levels of A2N0757 and A2N0647 are suspected to represent the dolomite aquifer.

The groundwater elevations in monitoring borehole A2N0647 recorded from 2003 to 2021 were deeper than in A2N0757. Overall, the water elevations in the Fountain West Karst Compartment are observed to be stable since 2003 onwards as indicated in Figure 4-14.

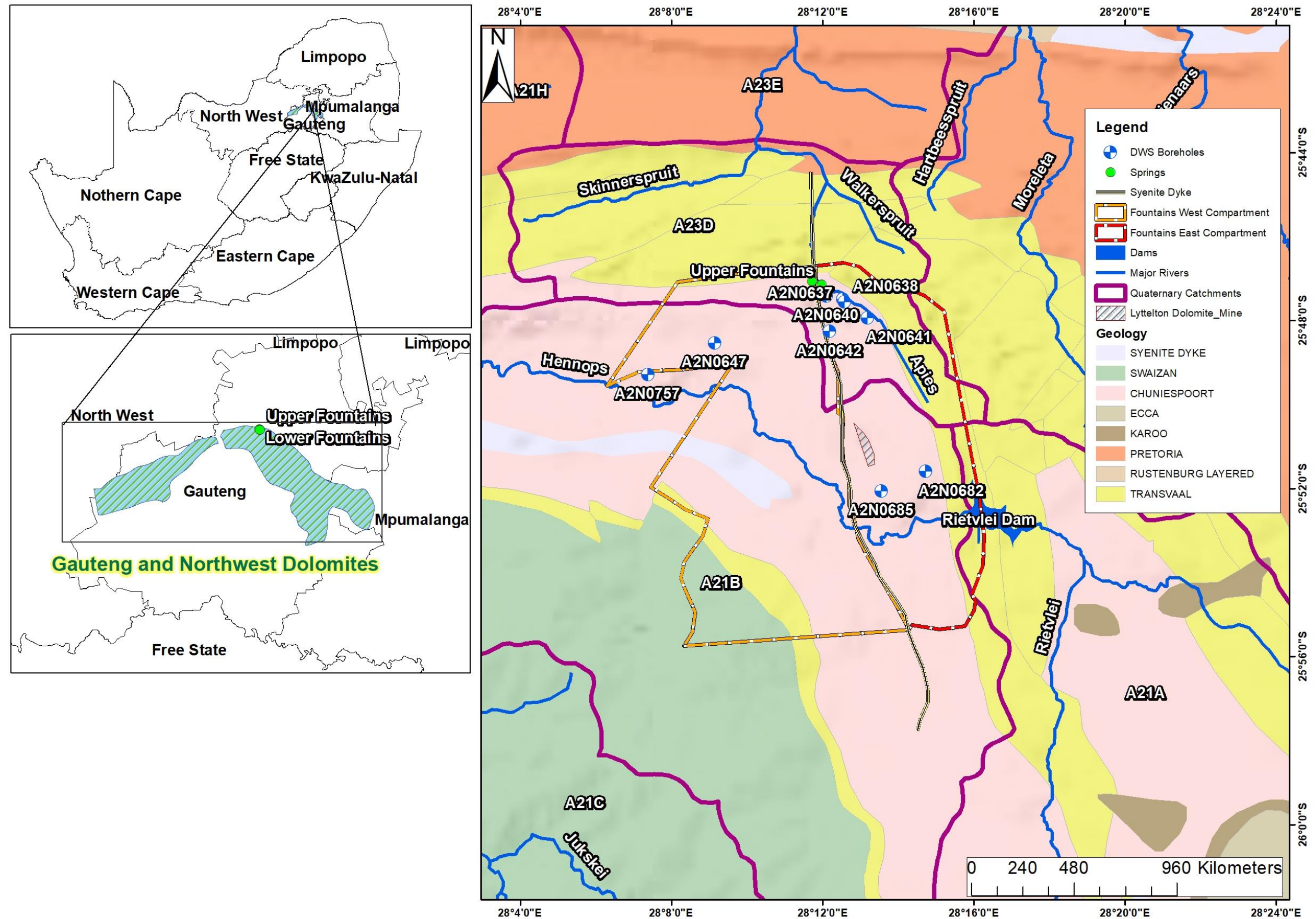


Figure 4-13: Map showing the locations of DWS monitoring boreholes within the Fountain East and West Karst Compartments divided by the syenite dyke.

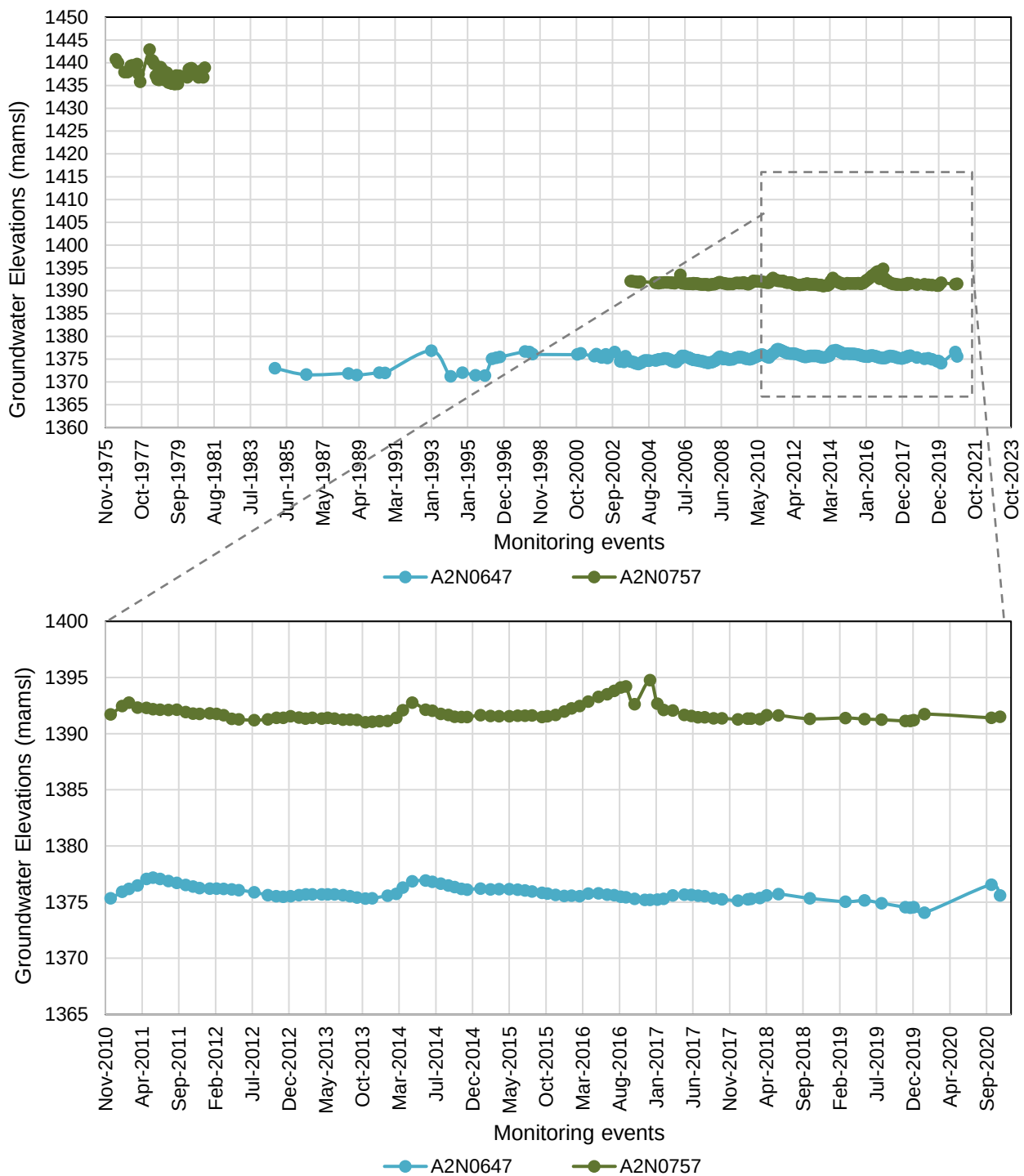


Figure 4-14: Temporal groundwater levels measured between 1975 to 2021 in boreholes (A2N0647 and A2N0757) installed into the West Karst Compartment. Zoomed in plot of the period from 2010 to 2020.

The groundwater elevations of boreholes within the Fountain East Compartment were similar and likely to represent the dolomite karst aquifer. The shallower groundwater elevations in A2N0685, ranging from 1427.19 mamsl to 1422.46 mamsl are suspected to be shallower due to the borehole being near the Hennops River and Rietvlei Dam and these could represent an alluvial aquifer.

The water levels within A2N0638, A2N0640, A2N0641 and A2N0642 ranging between 1392.25 mamsl to 1375.00 mamsl are likely representative of the deeper dolomite aquifer. The water levels in A2N0637 were shallower than the rest of the water levels within the Fountain East Karst Compartment, ranging between 1362.92 and 1384.01 mamsl. The water levels within A2N0642 are more erratic when compared to water levels in A2N0638, A2N0640, A2N0641 and A2N0642 as indicated in Figure 4-15.

The erratic groundwater levels in A2N0682, as indicated in Figure 4-15 could be due to groundwater abstraction, even though the water levels were only measured up to 2001. It is considered likely that the erratic water levels in A2N0682, located near the syenite dyke could be due to fracture flow associated with active abstraction and not dewatering at the nearby Lyttelton Dolomite Mine which was only established in 1998 (Bloomberg, 2023). The groundwater levels measured between 2010 and 2020 indicate no significant changes, and in general and as would be expected, the shallower groundwater levels are observed near the springs whilst deeper groundwater levels are observed further south away from the springs.

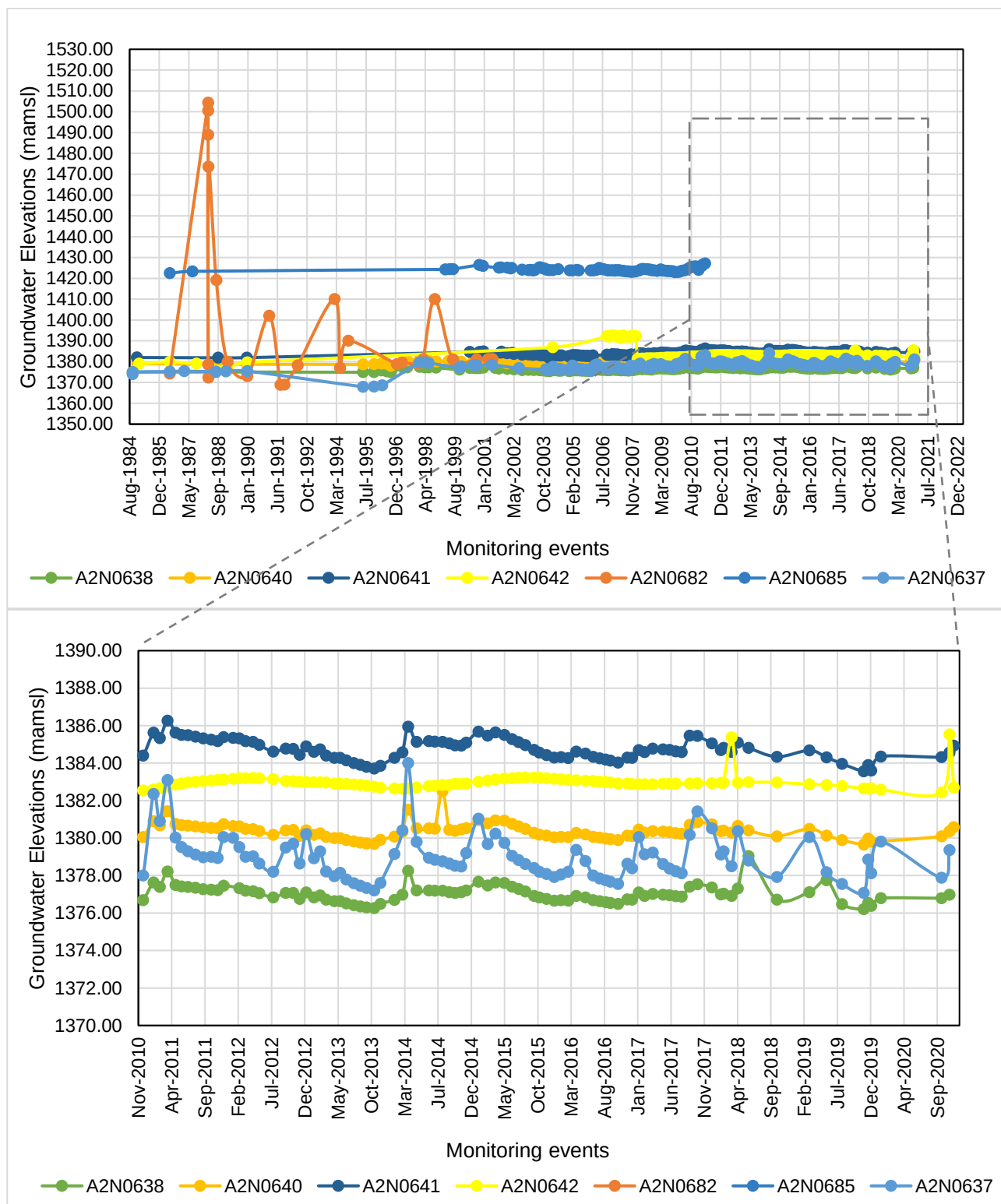


Figure 4-15: Temporal groundwater levels measured between 1975 to 2021 in boreholes installed into the East Karst Compartment

The statistical summary of groundwater levels in the Fountain East and West Karst Compartments is presented in Table 4.3. The groundwater levels in the Fountain West Karst Compartments measured between 1984 to 2020, were between 1371.20 mamsl and

1442.88 mamsl, whilst the average groundwater levels per borehole were 1375.36 mamsl and 1391 mamsl. In the Fountain East Karst Compartment, the groundwater levels measured within the same period were between 1367.92 mamsl and 1427.19 mamsl, with average groundwater levels per borehole were between 1376.68 mamsl and 1423.92 mamsl as indicated in Table 4.3.

The deeper water levels are indicative of the dolomite aquifer described to occur to maximum depths of up to 130 mbgl by Naidoo (2014). The median and maximum changes in groundwater levels between consecutive measurements were consistent in boreholes within the two compartments, except in borehole A2N0642 and A2N0757, considered to have the greatest maximum change of 11.10 m (January and February 2008) and 7.10 m (September 1977 and March 1978).

Table 4.3: Summary of descriptive statistics for groundwater levels within the Fountain East and West Karst Compartments

Station Number	Compartment	Period	Min (mamsl)	Max (mamsl)	Median (mamsl)	Median change (m)	Max change (m)
A2N0647	Fountain West	1984 – 2020	1371.20	1377.19	1375.36	0.11	5.64
A2N0757			1391.02	1442.88	1391.75	0.09	7.10
A2N0637	Fountain East	1984 – 2020	1367.92	1384.01	1378.18	0.77	10.97
A2N0638			1379.05	1379.05	1376.68	0.11	2.33
A2N0640			1377.89	1382.50	1380.07	0.11	2.69
A2N0641			1381.66	1386.27	1384.29	0.13	2.75
A2N0642			1377.30	1392.70	1382.91	0.04	11.10
A2N0685			1422.46	1427.19	1423.92	0.19	2.11

The average groundwater levels were contoured against surface elevation, using ArcGIS® to determine the hydraulic gradient and estimated flow direction. An Excel table with average groundwater elevations from each borehole was imported into ArcGIS® and the data was converted to point data with coordinates, borehole name and average groundwater elevation. The Kriging interpolation method was used to create a raster map of groundwater elevations. Kriging is a linear interpolation used when interpolating unknown data points between known data points. For the purposes of study, Kriging was used to calculate groundwater flow contours shown in Figure 4-16.

The general groundwater flow direction was generally towards the northwest and in line with surface topography which decreases towards the north.

In the Fountain East Karst Compartment, groundwater flow direction was mostly towards northwest as shown in Figure 4-16. The general groundwater elevation within the study area indicates that the headwaters are located south of the study area where higher surface elevations are observed, and the general groundwater flow direction is similar to flow calculated by Naidoo (2014). The deeper water table along the southern portion of the study area, near borehole A2N0685 could be due to increased groundwater abstraction resulting in a cone of depression.

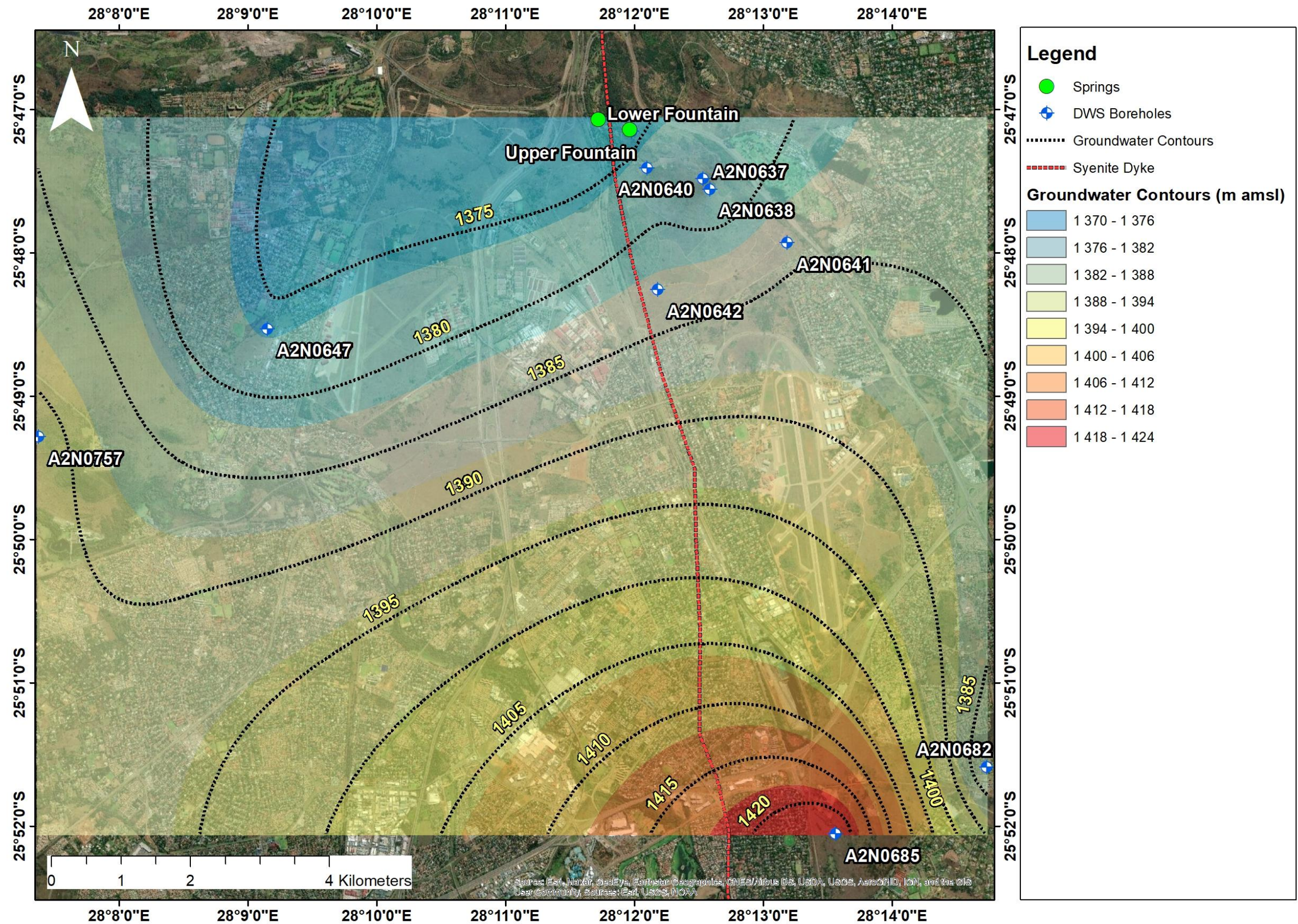


Figure 4-16: Groundwater contour map indicating flow directions within the study area

4.9 HYDROCHEMICAL CHARACTERISATION

The study conducted by Naidoo (2014) provides a more detailed discussion of the hydrochemical characterisation of the Fountain East and West Karst Compartments, and the information below provides a summary of the findings of the study conducted by Naidoo (2014).

The chemistry of groundwater from the Fountain East and West Karst Compartments indicates a calcium, magnesium-bicarbonate (Ca,Mg-HCO_3) water type, determined from available water quality data collected between 2007 to 2012 (Naidoo, 2014). Although Naidoo (2014) concluded that there is “significant” variation in the chemistry of the Upper and Lower Fountain, the chemistry data indicated calcium and magnesium as dominant cations in both springs whilst, bicarbonate is indicated as the dominant anion.

The average total dissolved solids (TDS) concentrations of the Upper Fountain, recorded between 2007 and 2012 were 270.65 mg/l and 318.29 mg/l in the Lower Fountain (Naidoo, 2014). The concentrations of anions and cations were slightly higher in the Lower Fountain when compared to the Upper Fountain but within a similar range as shown in Figure 4-17. The ions of concern not discussed in detail by Naidoo (2014), included the slightly higher chloride and sulphate concentrations within the Lower Fountain, potentially indicative of recharge from an external water source apart from precipitation, which according to Naidoo (2014), had on average a higher spring discharge of ~4 Ml/day when compared to the Lower Fountain.

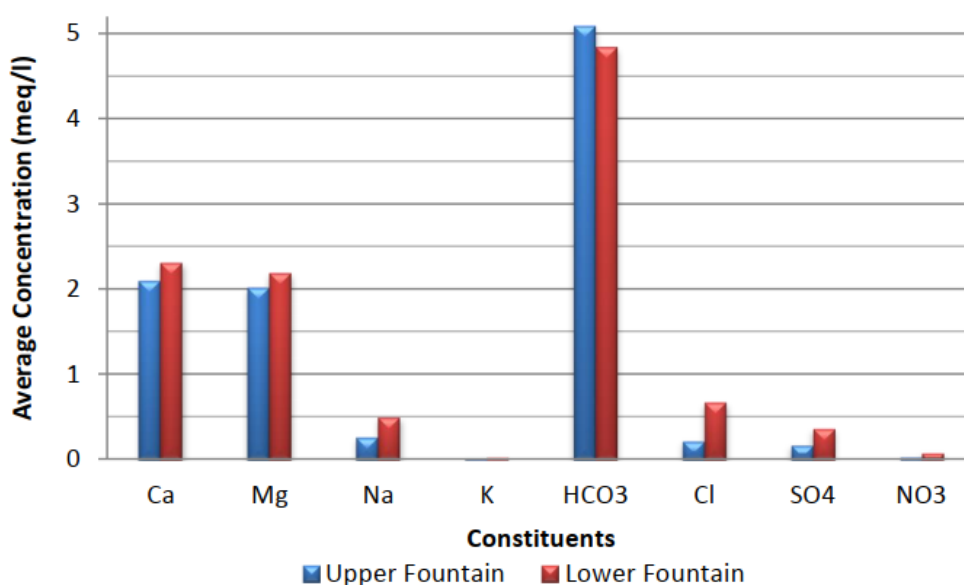


Figure 4-17: Average concentrations of cations and anions within the Upper and Lower Fountain measured between 2007 and 2012 (Naidoo, 2014)

4.10 DISCHARGE RATES OF THE FOUNTAIN SPRINGS

The CoT provided spring discharge data for events in 2016, 2018, 2019, 2020 and 2021 as indicated in Appendix A. The data was non-continuous/sporadic as indicated in Figure 4-18, due to power interruptions encountered during most monitoring events, resulting in the digital meter used to record readings not working.

Abdin et al. (2021) and Olarinoye et al. (2020) highlighted the inherent sporadic nature of spring discharge data on studies conducted across various countries, as a result of operational and logistical challenges. The data collected between July 2011 to September 2012 and February 2020 to April 2021 as highlighted in yellow in Figure 4-18, was deemed to be representative of a single hydrological cycle chosen for further assessment. The spring discharge data from July 2011 to September 2012 was selected to assess the potential erratic flows in the Lower Fountain Spring as indicated by Naidoo (2014), whilst the spring discharge from February 2020 to April 2021 was considered to have more monitoring points spread over the different seasons (wet and dry season), which was used to check if the erratic spring discharge in the Lower Fountain Spring were persistent beyond the period of July 2011 to September 2012.

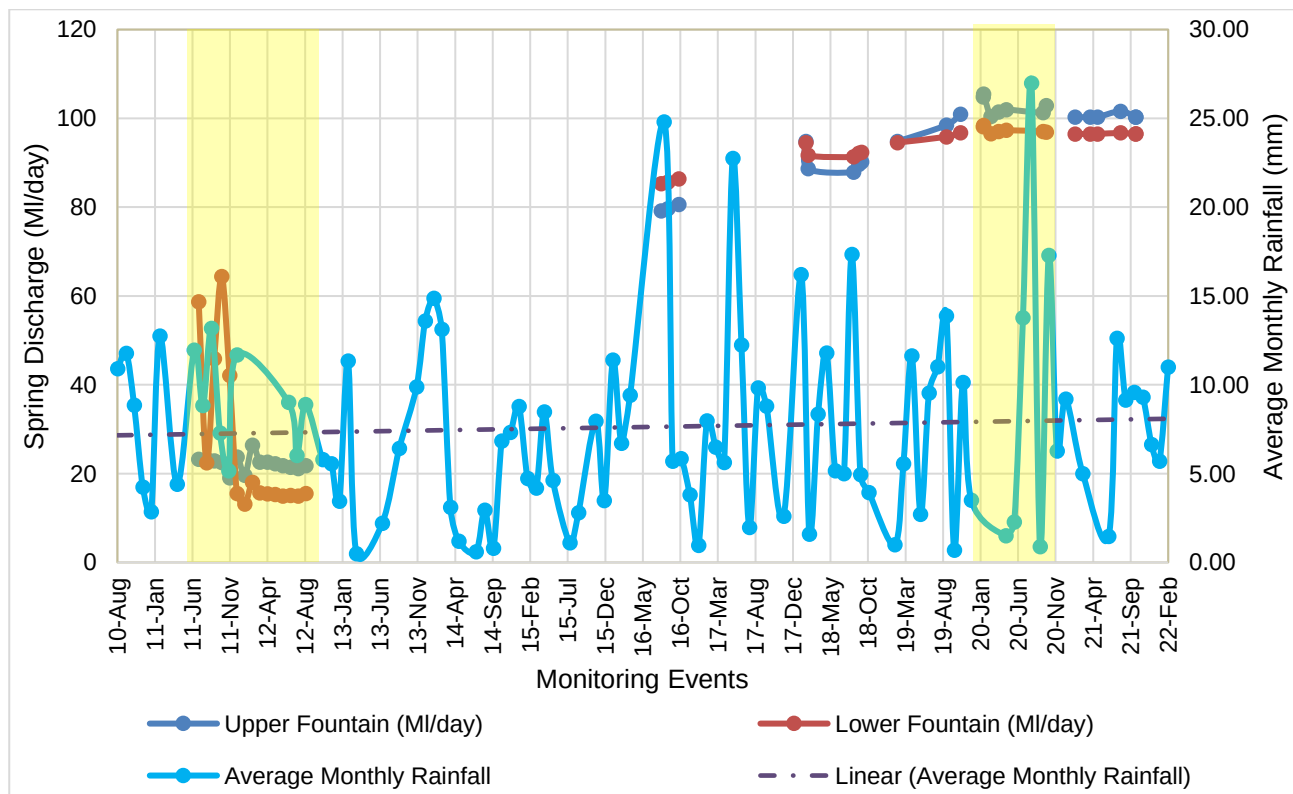


Figure 4-18: Monthly spring discharge rates of the Upper and Lower Fountain springs measured between July 2016 and October 2021

The discharge rates of the Lower Fountain spring were reportedly 4 MI/day on average higher than the Upper Fountain spring (Naidoo, 2014). The average spring discharge of the Lower Fountain was 25.81 MI/day between 2011 to 2012, and 97.17 MI/day between 2020 to 2021. The average spring discharge of the Upper Fountain Spring was 22.28 MI/day in 2011 to 2012 and 102.13 MI/day in 2020 to 2021.

The temporal spring discharge of the Lower Fountain is observed to be more erratic between 2011 and 2012, and shows no direct relationship with rainfall since higher spring discharges are noted in July 2011, September 2011 and February 2012 when rainfall is relatively lower than the prior event as shown in Figure 4-19. The spring discharge of the Upper Fountain is relatively stable with occasional erratic flows in November 2011 and February 2012, coinciding with the rainy season as shown in Figure 4-19.

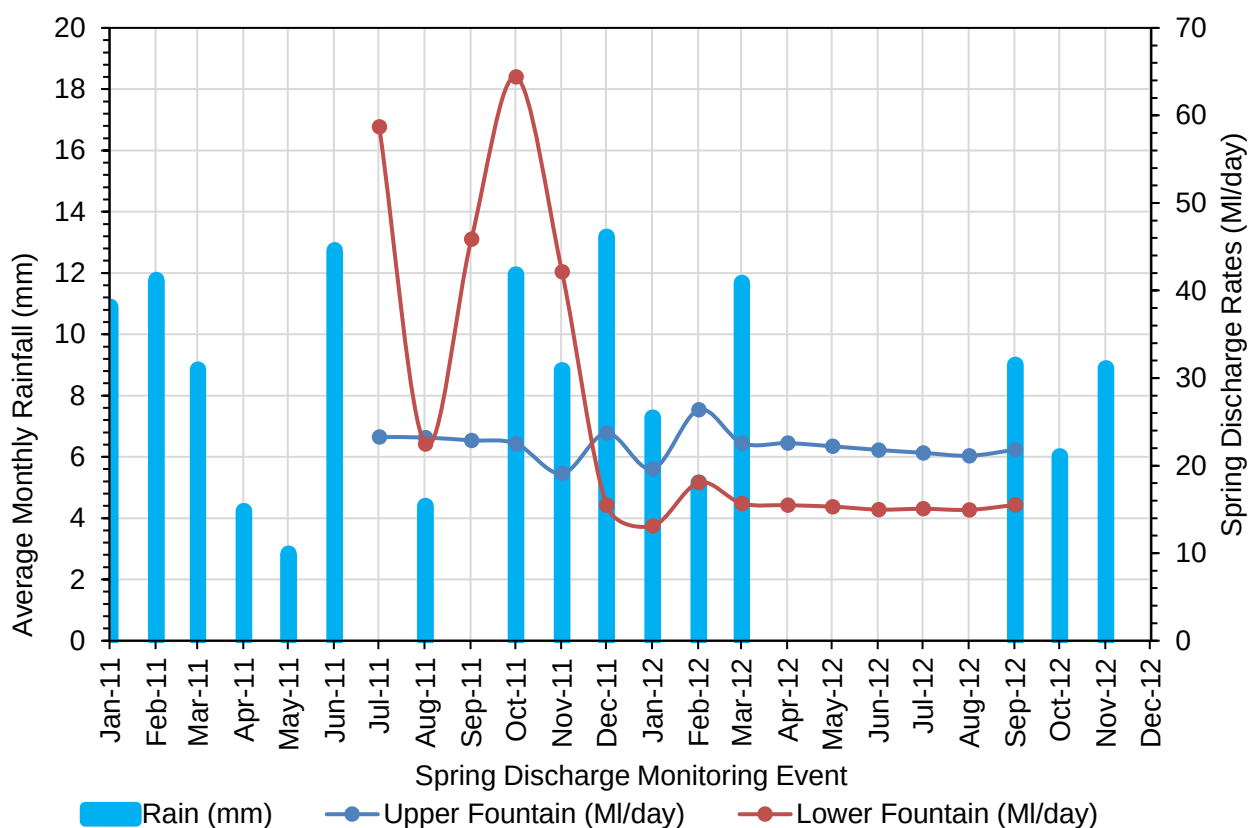


Figure 4-19: Monthly spring discharge rates of the Upper and Lower Fountain springs measured between July 2011 to September 2012

Between 2020 and 2021, the spring discharge of the Lower Fountain was more stable than the Upper Fountain as shown in Figure 4-20. The spring discharge of the Upper Fountain remained higher than the Lower Fountain by an average difference of 5 MI/day. A similar response in spring discharge is observed for the Upper and Lower Fountain springs,

although the data has gaps, the spring discharge show a direct relationship with rainfall in February 2020 and October 2020 as shown in Figure 4-20.

On average, the spring discharge of the Upper Fountain increased by 79.85 MI/day compared 2011 and 2012 spring discharges, whilst the spring discharge of the Lower Fountain increased by 71.36 MI/day compared to the 2011 and 2012 spring discharges. The spring discharge data for 2012 event and 2020-2021 events indicate a similar trend of peak flows between January and February. Additional peak flows for 2020 and 2021 spring discharge rates are observed in October whilst baseflow is observed between March and September as indicated in Figure 4-19 and Figure 4-20. Although increased spring discharge rates are observed in 2020 to 2021, the groundwater levels within the Fountain East and West Karst Compartments were not showing significant changes in 2020 and 2021.

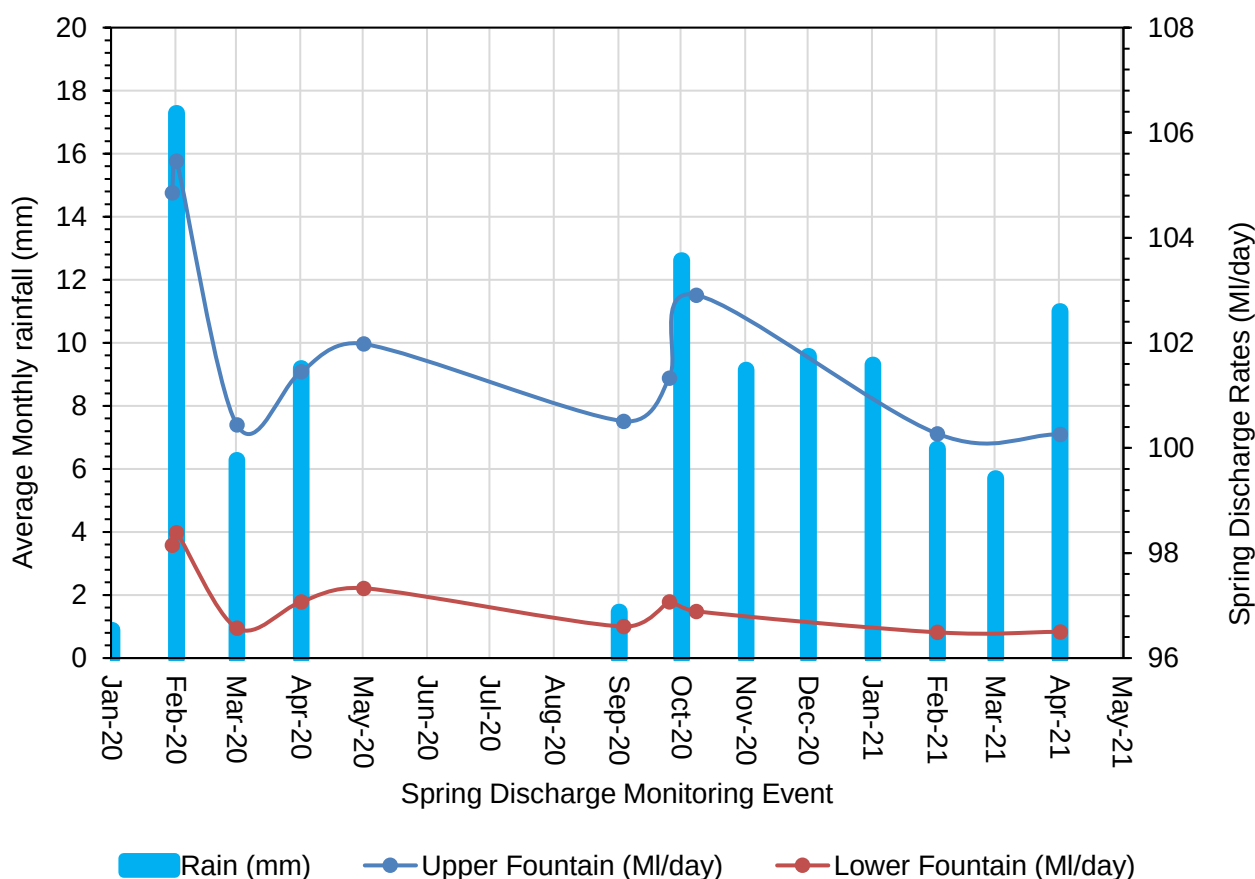


Figure 4-20: Monthly spring discharge rates of the Upper and Lower Fountain springs measured between January 2020 to February 2021

A summary of maximum and minimum spring discharge, number of measurements and mean discharge of the springs for 2011 to 2012, and 2020 to 2021 are presented in Table 4.4. The maximum spring discharge of the of the Lower Fountain Spring was higher in 2011

to 2012 when compared to a lower maximum spring discharge in 2020 to 2021 as indicated in Table 4.4.

A similar trend of maximum spring discharge is observed for minimum spring discharge from 2011 to 2012, and 2020 to 2021 as shown in Table 4.4. Generally higher spring discharge rates are observed for 2020 to 2021 when compared to 2011 to 2012, and this could be associated with generally higher rainfall observed during 2020 to 2021 as shown in Figure 4-19 and Figure 4-20.

Table 4.4: Summary of descriptive statistics for the Upper and Lower Fountain Springs

Spring	Period	$Q_{\max}$ (MI/day)	t_{event} (months)	$Q_{\min}$ (MI/day)	Q_{mean} (MI/day)
Lower Fountain	2011 to 2012	64.40	15	14.95	25.81
	2020 to 2021	98.39	10	96.50	97.17
Upper Fountain	2011 to 2012	26.38	15	19.09	22.28
	2020 to 2021	105.46	10	100.27	102.13

A single karst recession/event was considered to be represented by single event quick flow (higher spring discharge) followed by a successive base-flow (lower spring discharge), as shown in Figure 5-1 and Figure 5-2.

5 RESULTS

5.1 INTRODUCTION

This chapter describes the results of methods applied to assess possible causes of erratic spring discharge within the Lower Fountain Spring.

5.2 SPRING HYDROGRAPH ANALYSIS AND DEGREE OF KARSTIFICATION

The method of assessing the DK followed in this chapter is presented in Section 2.5.1 and Section 3.5.1. The DK was determined using spring discharge rates from 2011 to 2012 and 2020 to 2021, using Equation 3 and spring hydrograph data indicated in Figure 4-19 and Figure 4-20 in Section 4.10. The peak discharge, minimum discharge, time at which the peak discharge is observed including total time of a single spring hydrograph were used as input values to calculate the degree of karstification.

The graphical representation of how the input parameters to Equation 6 were determined is presented in Figure 5-1, where a peak flow of 64.40 ML ($Q_{\max}$), experienced during the fourth month ($t_{\max}$) of a 6 monthly (t_{event}) event was noted for the spring discharge data of the Lower Fountain Spring between July 2011 and December 2011 where the minimum spring discharge at the beginning of the rising limb was 22.5 ML ($Q_{\min}$). The information extracted from Figure 4-19 and Figure 4-20 is presented in Table 5.1.

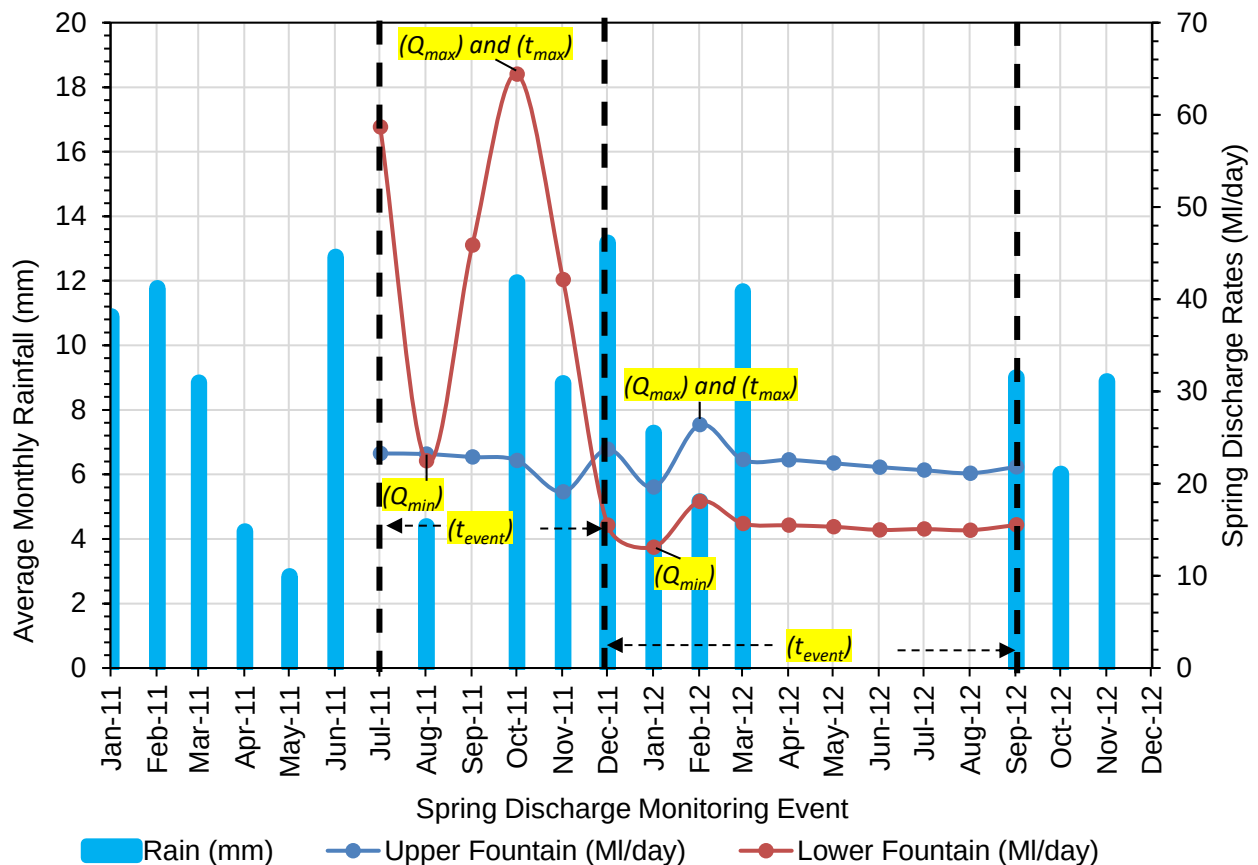


Figure 5-1: An example of the graphical representation of input parameters used to calculate the degree of karstification within the Fountain West Compartment as determined from the Spring Discharge data of the Lower Fountain Spring for events between 2011 to 2012.

The graphical representation of how the input parameters to Equation 6 were determined is presented as Figure 5-2, where a peak flow of 98.39 ML (Q_{max}), experienced during the second month (t_{max}) of a 5 monthly (t_{event}) event was noted for the spring discharge data of the Lower Fountain between February 2020 and April 2021 where the minimum spring discharge at the beginning of the rising limb was 96.57 ML (Q_{min}). The information extracted from Figure 4-19 and Figure 4-20 is presented in Table 5.1.

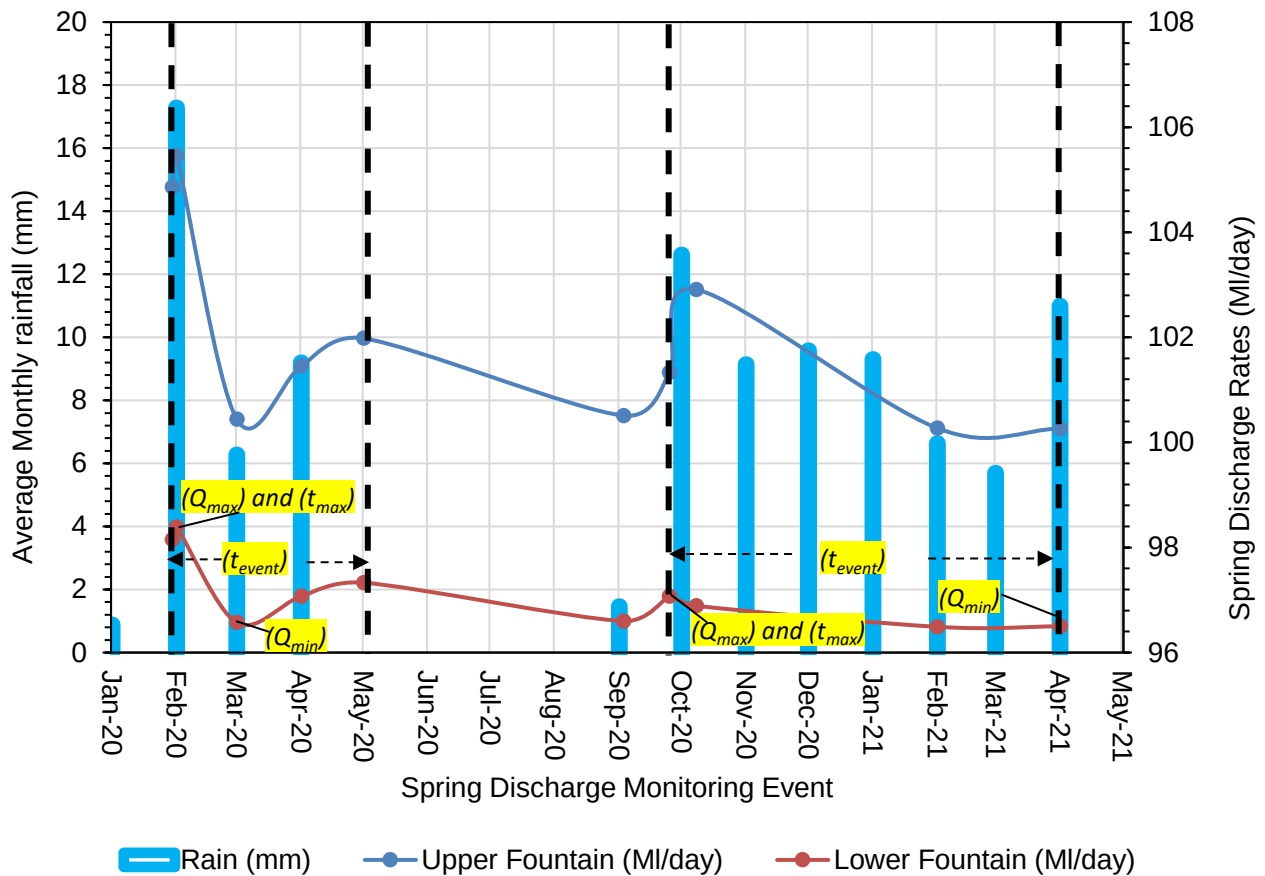


Figure 5-2: An example of the graphical representation of input parameters used to calculate the degree of karstification within the Fountain West Compartment as determined from the Spring Discharge data of the Lower Fountain Spring for events between 2020 to 2021

The DK for 2011 (Upper Fountain Spring) and 2012 (Lower Fountain Spring) spring discharge data were relatively higher than in 2020 and 2021. The highest DKs were noted in 2012 and these were between 6.20 for the Lower Fountain Spring, and 7.14 for the Upper Fountain Spring. Slightly lower DKs of 3.73 and 4.29 were determined from 2011 spring discharge data of the Upper and Lower Fountain Springs respectively. Malík and Vojtková (2012) have shown that the DK can be described using a 10-degree scale, with the first-degree scale associated with lower DKs, and the tenth scale associated with higher DKs. Malík and Vojtková (2012) suggests that a further step of hydrograph separation should be undertaken to differential proportional flows from different compartments and refine the sub-flow regimes contributing to the overall discharge. The hydrograph separation method is considered more reliable than a combined single recession curve, although more dataset is required to effectively conduct hydrograph separation (Malík and Vojtková, 2012).

The computed DKs for 2011 and 2012 spring discharge data were compared with sub-regimes with similar DKs from the literature, as presented by Malík and Vojtková (2012),

which indicated that the computed DKs are similar to karst environments with dual flow and high degree of karstification.

Lower DKs of between 1.21 and 1.71 were determined for the Upper and Lower Fountain Springs using 2020 and 2021 spring discharge data. The overall DKs indicate higher DKs between 2011 to 2012 when compared to DKs from 2020 to 2021. The lower degrees of karstification compares favourably with less complex single laminar flow regimes associated with the matrix and fissures of a less karstified aquifer. The overall DKs indicate higher DKs between 2011 to 2012 when compared to DKs from 2020 to 2021. In reality, the shift from higher DKs to lower DKs would mean that the epikarst contributed significantly to the overall in 2011 to 2012 when compared to 2020 and 2021 or the 2011 to 2012 spring discharge data was erroneous. The determination of DKs from the available spring discharge data has highlighted evidence of severe disturbance in the release of groundwater from the Lower and Upper Fountain Springs between 2011 and 2012.

The DKs calculated from recession curves of the Upper and Lower Fountains Springs were compared with DKs in the literature as reported by Malik and Vojtková (2012). The higher DKs calculated from spring discharge data of July 2011 and September 2012, compared favourably with turbulent flow sub-regimes whilst DKs of spring discharge data from February 2020 and April 2021 compared favourably with laminar flow sub-regimes.

Although the sub-regimes of turbulent and laminar flows described by Malik and Vojtková (2012) are mostly associated with high degree of faulting, this is considered unlikely in the study since limited faulting exists within the karst compartments. It is likely that the epikarst contributed significantly to the overall flow of groundwater to the springs in 2011 and 2012 when compared to 2020 and 2021, where less contribution from the epikarst was likely experienced.

Table 5.1: Flow conditions within Upper and Lower Fountain according to parameters of the recession curve (Modified from Malík and Vojtková, 2012)

Spring	Period	Q _{max} (Ml/day)	t _{event} (months)	Q _{min} (Ml/day)	t _{peak} (months)	DK (unitless)	Groundwater Flow sub-regime types	Characteristics of karstification degree
Lower Fountain	Jul-11 to Dec-11	64.4	6	22.5	4	4.29	“Discharge hydrograph is composed of a sub-regime with turbulent flow and a sub-regime with laminar flow”	“Aquifer with anticipated existence of crushed water-bearing zone (e.g., fault zone) or by dense network of open small fissures in combination with simple, partly (or occasionally) phreatic conduit system of considerable extent (e.g., with open karstified fault in the vadose zone)”
	Jan-12 to Sep-12	18.07	9	13.11	2	6.20	“Very complex discharge regime, a combination of two sub-regimes with turbulent flow and two sub-regimes with laminar groundwater flow. Discharge sub-regimes with turbulent flow are of short-term influence in comparison with overall groundwater discharge”	“Extensive disruption and disintegration of rock environment, with majority of open, medium size, both not karstified and karstified fissures in the phreatic zone of the fissure karst aquifer and with smaller influence of connected conduits”
	Feb-20 to May-20	98.39	5	96.57	3	1.70	“Single laminar sub-regime, higher recession coefficients. Maillet (1905) exponential formula applicable”.	“Usually, tectonic faults and shear zones filled with crushed material, with high buffering capability in relation to discharge. Mainly deeper groundwater circulation”.
	Sep-20 to Apr-21	97.07	4	96.49	3	1.34		
Upper Fountain	Jul-11 to Dec-11	23.72	6	19.09	2	3.73	“Combination of two or more sub-regimes with merely laminar flow characterised by different discharge. Coefficients”	“Aquifer with irregularly developed fissure network, with majority of open macro fissures, also with possible presence of karst conduits of limited extent. In extreme cases, even short-term turbulent flow might occur in this type of rock environment”
	Jan-12 to Sep-12	26.38	9	19.62	2	7.14	“Very complex discharge regime, a combination of two sub-regimes with turbulent flow and two sub-regimes with laminar groundwater flow. Discharge sub-regimes with turbulent flow are of short-term influence in comparison with overall groundwater discharge”	“Extensive disruption and disintegration of rock environment, with majority of open, medium size, both not karstified and karstified fissures in the phreatic zone of the fissure karst aquifer and with smaller influence of connected conduits”
	Feb-20 to May-20	101.98	6	100.44	5	1.21	“Single laminar sub-regime, higher recession coefficients. Maillet (1905) exponential formular”.	“Usually, tectonic faults and shear zones filled with crushed material, with high buffering capability in relation to discharge. Mainly deeper groundwater circulation”.
	Sep-20 to Apr-21	102.91	5	100.51	3	1.71		

5.3 RECESSION CURVE ANALYSES

The recession curve analysis was conducted as indicated in Section 2.5.1 and Section 3.5.2. A graphical representation of dominant flows within the Upper and Lower Fountain Springs is presented in Figure 5-3 and Figure 5-4. A line of best fit was chosen between peak and baseflow of a single recession for spring discharge data of 2011 to 2012 and 2020 to 2021. The line of best fit was selected in such way that it captures the peak flow and baseflow of a single recession as indicated in the assessment conducted by Torresan et al. (2020).

The spring discharge data from 2011 to 2012 and 2020 to 2021 was used to determine the order of magnitude of recession coefficients. The different orders of recession coefficients were determined as shown in Figure 5-3 and Figure 5-4, using the widely applied Maillet (1905) equation (Equation 4) presented in Chapter 2. The orders of recession considered when determining the different recession coefficients are presented in Table 5.2.

The determined recession coefficients were interpreted according to the methodology presented by Torresan et al. (2020), which indicates higher recession coefficients with an order of magnitude of 10^{-1} to represent rapid conduit flow, whilst recession with an order of magnitude of 10^{-2} represent dual flow (matrix and conduit flow), and recession coefficients with an order of magnitude of 10^{-3} represent slow diffuse flow.

Table 5.2: Summary of input data used to calculate recession coefficients.

Spring	Period	Order of Recession coefficient (a)	Q_0 (MI/day)	t_0 (Months)	Q_t (MI/day)	t (Months)	Δt
Lower Fountain	2011 to 2012	a_1	64.40	10	13.11	13	3
	2011 to 2012	a_2	18.07	2	15.51	9	7
	2020 to 2021	a_1	98.15	1	96.6	9	8
	2020 to 2021	a_2	97.07	9	96.50	4	5
Upper Fountain	2011 to 2012	a_1	23.27	7	19.62	13	6
	2011 to 2012	a_2	22.59	3	21.81	9	6
	2020 to 2021	a_1	104.86	1	100.51	9	8
	2020 to 2021	a_2	102.91	10	100.26	4	6

The recession coefficients calculated from spring discharge data from 2011 and 2012 indicated a combination of conduit dominated flow (during peak discharge) and mixed flow (during the baseflow) within the Fountains West Karst Compartment associated with the Lower Fountains Spring), whilst mixed and diffuse (matrix dominated flow) flows were

observed within the Fountains East Karst Compartment (associated with the Upper Fountains Spring) as shown in Figure 5-3.

The recession coefficients of spring discharge data from 2020 and 2021 indicated diffuse flow as the dominant flow within the Fountain East and West Karst Compartments as shown in Figure 5-4.

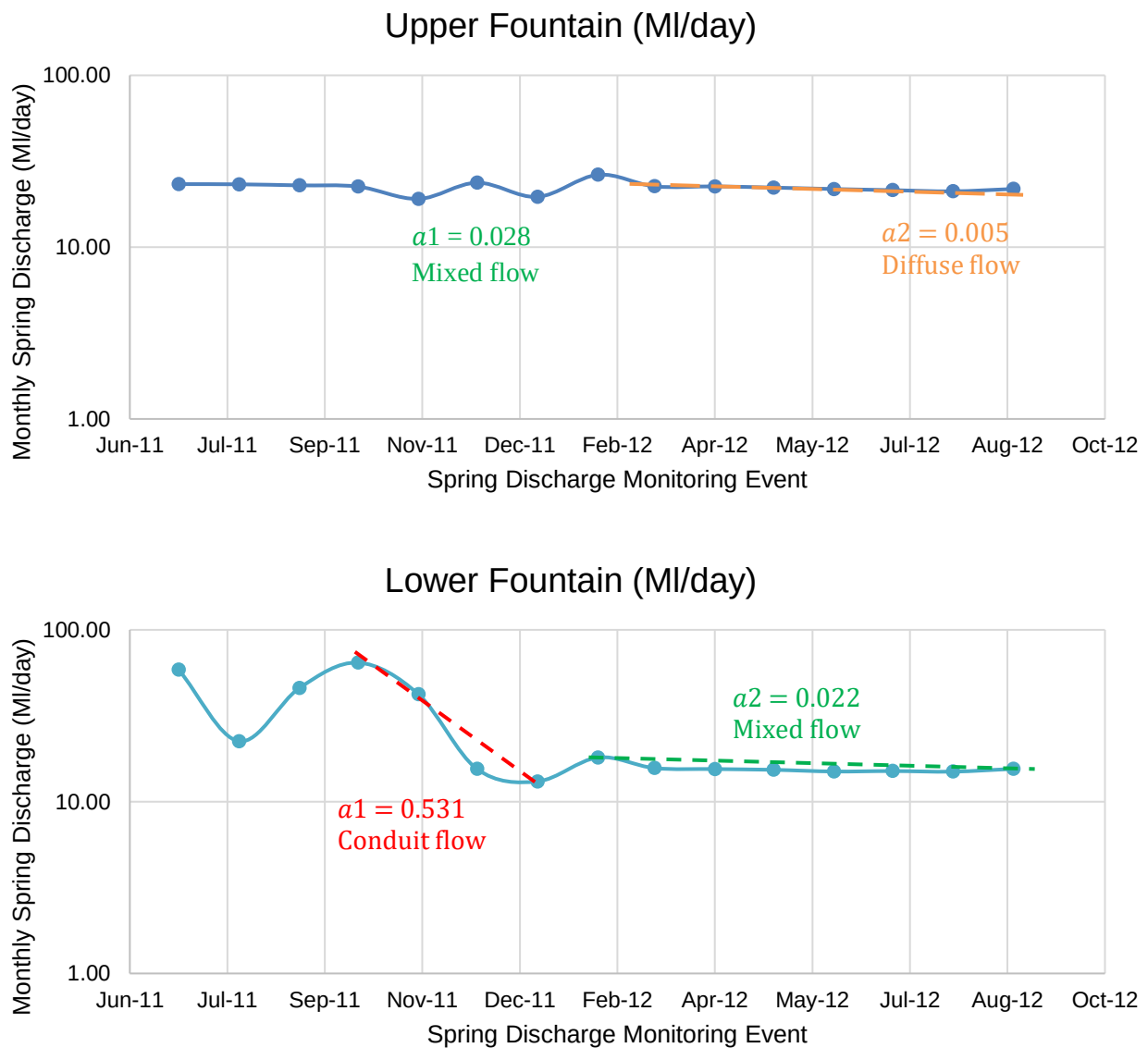


Figure 5-3: Recession curve analyses of spring discharge from the Upper and Lower Fountain Spring for 2011 to 2012 events

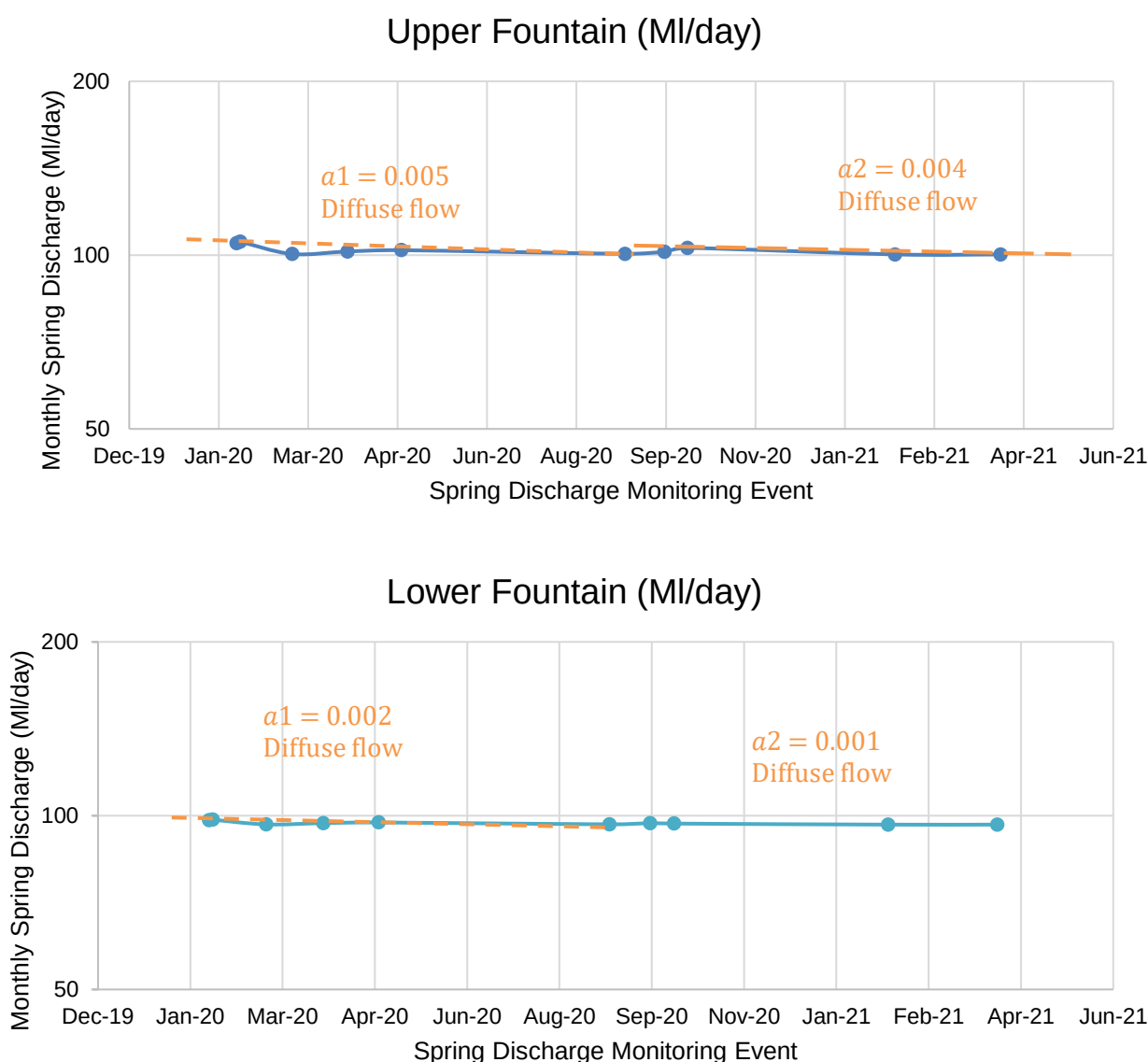


Figure 5-4: Recession curve analyses of spring discharge from the Upper and Lower Fountain Spring for 2020 to 2021 events

The determination of recession coefficients using spring discharge data from 2011 to 2012 and 2020 to 2021 was able to indicate that the more turbulent flow conditions controlled by the movement of groundwater through conduits was associated with peak spring flow (within the Fountains West Karst Compartment only) whilst, mixed (turbulent to laminar flows) and diffuse (laminar) flows controlled by the movement of groundwater through conduits, fractures and the matrix were dominant flows associated with baseflow in 2011 and 2012. In 2020 and 2021, the groundwater flow regimes within the Karst compartments were mostly stable and of diffuse nature (laminar) during peak both peak flow and baseflow of the springs.

5.4 RELATIONSHIP BETWEEN SPRING DISCHARGE, RAINFALL AND GROUNDWATER LEVELS

The Cross-Correlation Factor (CCF) is applied as discussed in Sections 2.5.2.1 and 3.5.1. The correlograms of rainfall versus spring discharge were computed to assess the influence of rainfall on spring discharge as presented in Figure 5-5.

The cross-correlation assessment considered one hydrological cycle (i.e., 12 months), a default displacement or lag of 1 between the input and output time series. The truncation of the data was by default at 6 months which is half of the total time series. The rainfall data was averaged to monthly rainfall data for comparison with monthly spring discharge and groundwater level data.

The maximum shift between the independent (rainfall) and dependent (spring discharge) variables was up to a lag of 6, corresponding to a period of 6 months. Sarker and Fryar (2022) and Guo *et al.* (2021) indicated that positive correlation is observed for correlation coefficients above 0.2.

A cross correlation of +1 at a specific lag of the correlogram indicates perfect correlation between the rainfall on the response of the spring (e.g., a more positive correlation coefficient at a lag of 1, corresponding to 1 month suggests that the effect of rainfall on spring discharge is prolonged by 1 month). In the case of karst aquifers, this could indicate higher residence of precipitation in the vadose zone. The magnitude of the cross-correlation function is proportional to the strength of the correlation.

A positive correlation is observed when the correlogram exceeds a correlation coefficient of 0.2. The exceedance of a correlation coefficient of 0.2 indicate a positive correlation between the input (rainfall) and output (spring discharge) variables. Positive correlations were observed for lags of -4, -2 and 3 for the Upper Fountain Spring discharge of 2011 to 2012, corresponding to 4 (lag of -4) and 2 (lag of -2) months before it rains; to 3 months (lag of 3) after it has rained.

No positive correlation above a correlation coefficient of 0.2 was observed for 2020 to 2021 spring discharge data. The positive cross-correlation coefficients of the Upper Fountain Spring (2011 – 2012) at a 3, provide evidence of a delayed response from the spring following a rainy event, indicative of allogenic recharge to Fountain East Karst Compartment.

Positive correlations were also observed for rainfall versus spring discharge from the Lower Fountain Spring (2011 – 2012) at lags of 1 (1 month), 2 (2 months) and 5 (5 months),

providing evidence of rainfall affecting spring discharge after 1, 2 and 5 months. The delayed effect of rainfall to spring discharge of the Lower Fountain Spring could suggest that recharge to the Fountain West Karst Compartment is afar.

The correlograms of rainfall versus spring discharge of the 2020 and 2021 monitoring events indicated a slight positive correlation at a lag of 2.5, providing evidence of rainfall affecting spring discharge after 2.5 months further confirming evidence of allogenic recharge to the aquifer.

The lower positive correlation between rainfall and spring discharge data from 2020 and 2021 could possibly be indicative of another source of constant recharge buffering the effect of rainfall to the aquifer, such as surface water bodies or even the golf courses identified within the study area as sources of recharge to the aquifer.

Cross-correlations of groundwater levels from 2020 and 2021 events were not computed due to insufficient data (only four readings collected in 2020 due to travel restrictions associated with the COVID pandemic) from the DWS monitoring boreholes.

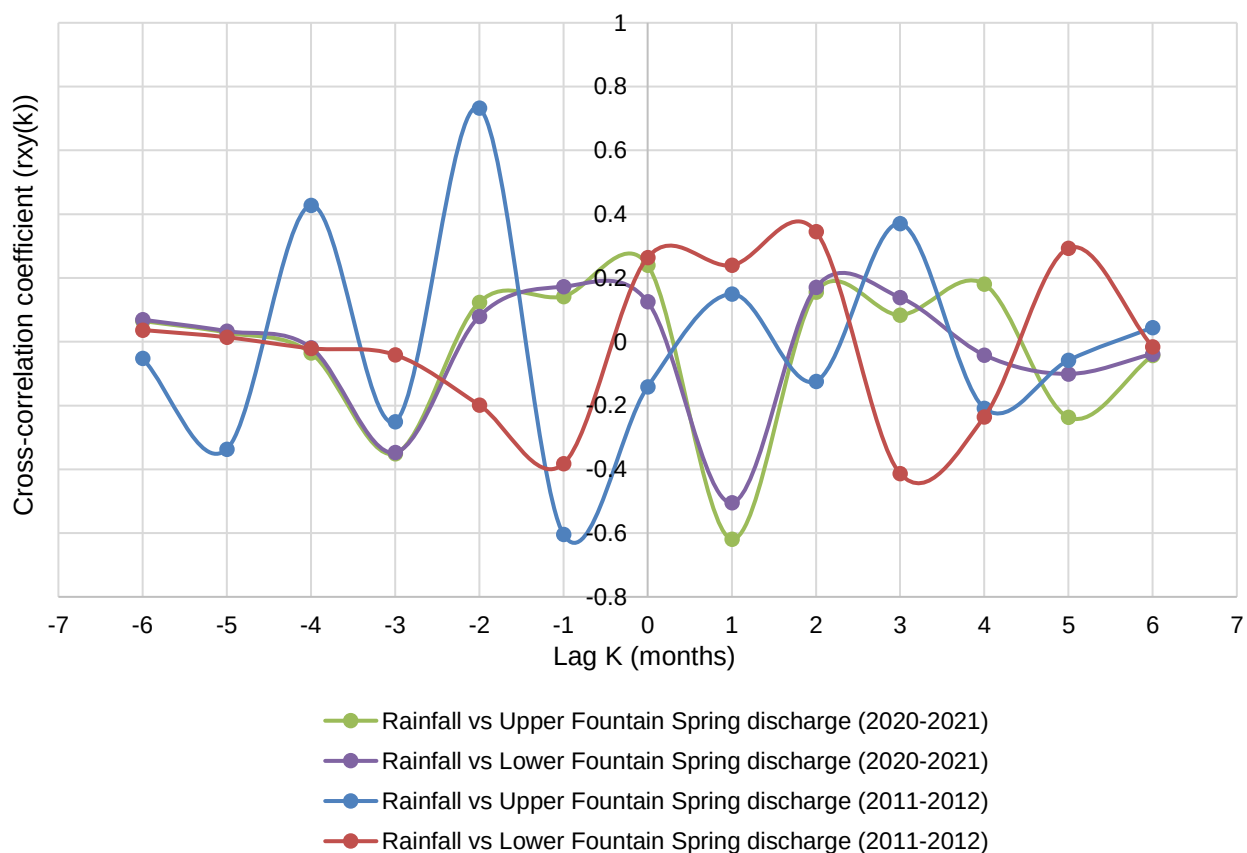


Figure 5-5: Cross-Correlation coefficients of rainfall as input and spring discharge of the Upper and Lower Fountain Springs as output for events between 2011 to 2012 and 2020 to 2021

The correlograms of rainfall versus groundwater levels were computed to assess the influence of rainfall on groundwater levels within the Fountain East and West Karst Compartments as presented in Figure 5-6. The correlograms indicated positive correlations at lags of 1 and 3, corresponding to 1 and 3 months after it has rained, suggesting input from allogenic recharge and prolonged residence time of recharge in the epikarst prior to being stored in the Fountain East Karst Compartment feeding the Lower Fountain Spring.

The correlogram of rainfall against water levels in boreholes A2N0637, A2N0638 and A2N0640 had the most positive correlations, showing a greater influence of recharge from rainfall to changes in groundwater levels (i.e. storage is mostly replenished by recharge from rainfall).

Similar positive correlations observed for boreholes A2N0637, A2N0638 and A2N0640, were observed for A2N0641, however, these were slightly less positive at lags of 1 and 3 months, indicating a slightly lower influence of rainfall on changes in groundwater levels as shown in Figure 5-7. The slightly lower correlation coefficients between rainfall and groundwater levels in A2N0641 could indicate input from other sources of influences such as surface water features that are affecting changes in groundwater levels.

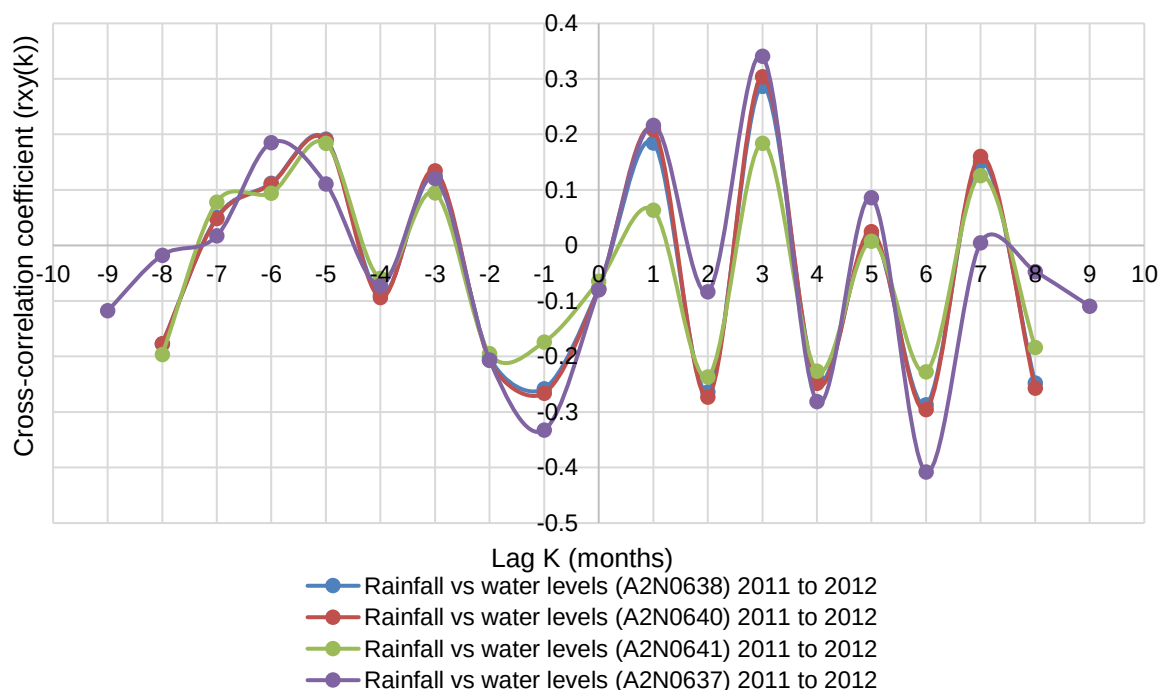


Figure 5-6: Cross-Correlation coefficients of rainfall as input and water levels in boreholes A2N0637, A2N0638, A2N0640 and A2N0641 within the Fountain East Compartment as output for events of 2011 to 2012 computed up to a lag of 8 equivalent to 8 months

The correlograms of rainfall against groundwater levels within the Fountain West Karst Compartment indicated no positive correlations (i.e., correlation coefficient above 0.2) for A2N0647 and A2N757, suggesting that recharge to the aquifer could be much further away from the aquifer or there are other sources of recharge to aquifer apart from rainfall. The most obvious surface water feature is the Hennops River, considered to be an important source of recharge, through baseflow to the Fountain West Karst.

The cross correlation of rainfall and water levels was able to show that rainfall is the main source of recharge to the Fountain East Karst Compartment whilst, other sources such as surface water features could be more important sources of recharge to the Fountain West Karst Compartment. The results were able to show that both compartments are recharged from afar (i.e. allogenic recharge).

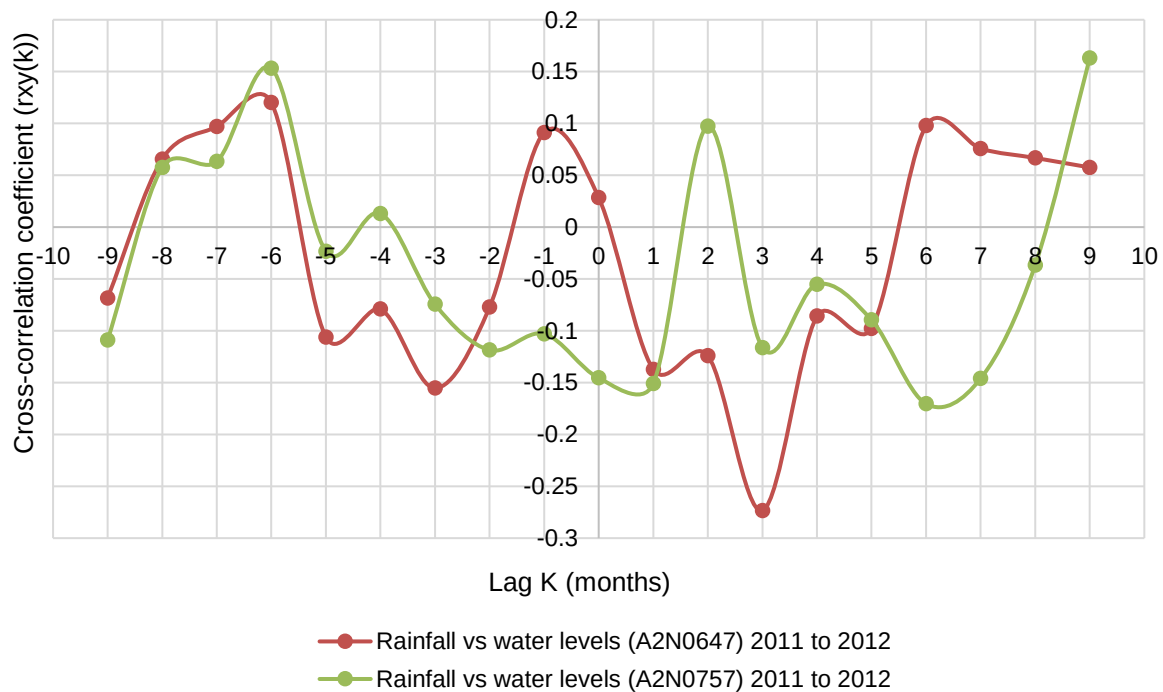


Figure 5-7: Cross-Correlation coefficients of rainfall as input and water levels in boreholes A2N0647 and A2N0757 within the Fountain West Compartment as output for events of 2011 to 2012, computed to lags of 9 equivalent to 9 months

5.5 MEMORY EFFECT AND GROUNDWATER STORAGE

The Auto-Correlation Factor (ACF) is applied as discussed in Sections 2.5.2.1 and 3.5.3.2, to assess the delayed version of a time series with the non-delayed version of the same time series. Similar to Cross-Correlation, the Auto-correlations of groundwater levels from 2020 and 2021 events were not computed due to insufficient data (only four readings collected in

2020 due to travel restrictions associated with the COVID pandemic) from the DWS monitoring boreholes.

The ACF is used in the field of karst hydrogeology to provide information on the storage capacity of karst aquifers through the assessment of linear dependency between two successive values of the original and delayed version of the time series (Denić-Jukić, 2020). Sarker and Fryar (2022) and Guo et al. (2021) indicated that positive correlation is observed for correlation coefficients above 0.2, with steeper auto correlograms indicating a more positive auto-correlation and a strong linear dependency between successive readings.

The spring discharge data used for ACF was from 2011 to 2012 (i.e., two hydrological cycles) and 2020 to 2021 (i.e., two hydrological cycles) events, including groundwater levels from the Fountain East and West Karst Compartments from 2011 to 2012 only.

The ACF of the correlogram of the Upper Fountain Spring for data collected in 2011 to 2012 reaches a correlation coefficient of 0.2 within 2 months whilst no correlation is observed for spring discharge from 2020 to 2021, indicating that the release of groundwater within the Fountain East Karst Compartment at the springs is not constant as indicated in Figure 5-8.

The observation of correlation at a lag of 2 indicates relatively consistent spring discharge within the Upper Fountain Spring over a short period in 2011 to 2012, likely due to the presence of a surface water features acting as sources of constant recharge to the aquifer at the time. Negative auto-correlations observed at a lag of 3 for 2011 to 2012 data and a lag of 5 for 2020 to 2021 data suggest that the measured spring discharge data has no linear dependency, and this could be during periods of peak flow transitioning to baseflow or vice-versa.

Groundwater levels from the Fountain East Karst Compartment reach an auto-correlation coefficient of 0.2 at a lag of 3 for A2N0640 and a lag of 4 for A2N0638 and A2N0640 providing evidence of a higher groundwater storage capacity within the Fountain East Karst Compartment as shown in Figure 5-8.

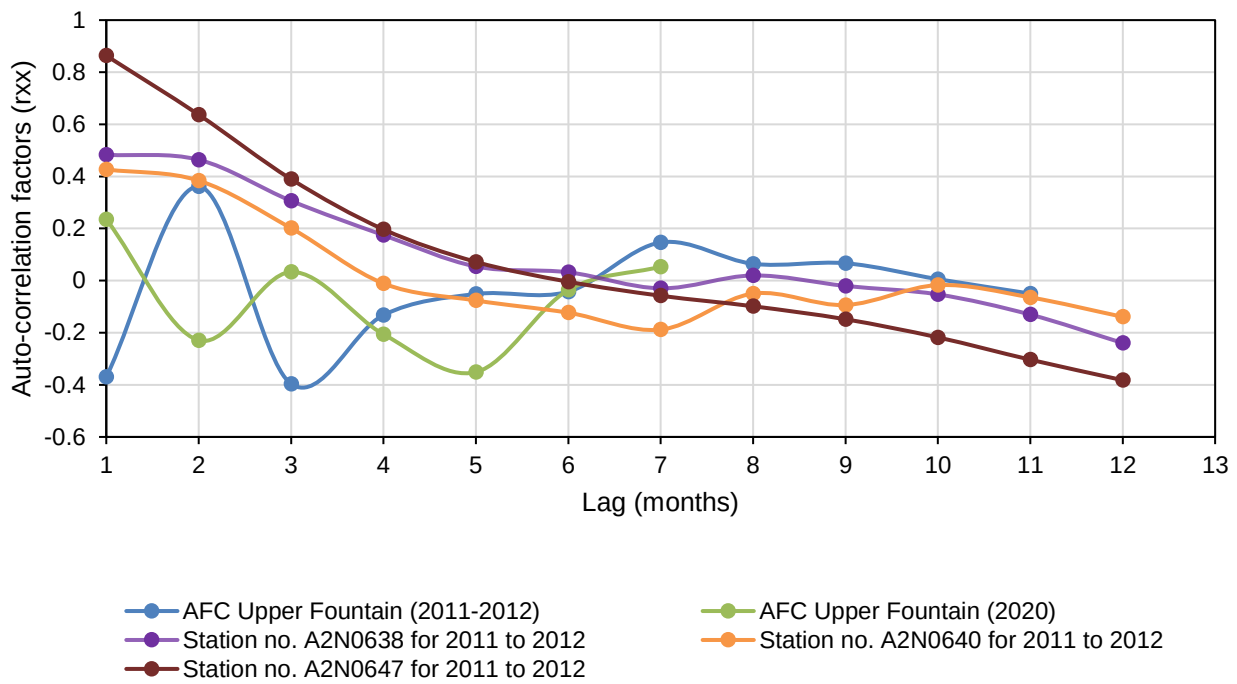


Figure 5-8: Auto-Correlation functions of spring discharge from the Upper Fountain Spring and water levels of the Fountain East Compartment for 2011 and 2012

The auto-correlation functions of spring discharge data from the Lower Fountain Spring measured between 2011 to 2012 reaches a correlation coefficient of 0.2, indicative of memory effect at a lag of 3.5 which is equivalent to 3.5 months. The memory effect indicates evidence of a consistent release (i.e. higher memory effect) from the Fountain East Karst Compartment over a short period of time (3 months) as indicated in Figure 5-9. The correlogram of spring discharge data collected between 2020 and 2021 from the Lower Fountain Spring indicate no positive correlation.

The correlogram of groundwater levels for 2020 and 2021 could not be determined since no groundwater level data was available. Negative correlations were observed for spring discharge data from the Lower Fountain Spring collected between 2011 and 2012 at lags of 9 and 10 suggesting more random (on a smaller scale) spring discharge over time.

Higher correlations are observed for groundwater levels within the Fountain East Karst Compartment and diminishes to below 0.2 at a lag of 4 for water levels in A2N0647, and a lag of 6 for water levels in A2N0757, indicating higher storage capacity over longer periods of 4 and 6 months within the Fountain West Karst Compartment. The overall auto-correlations of the Upper Fountain Spring and Fountain West Karst Compartment indicates evidence of higher storage (i.e., higher memory effect) in the aquifer however, the release of groundwater through the spring is mostly random (i.e., low memory effect).

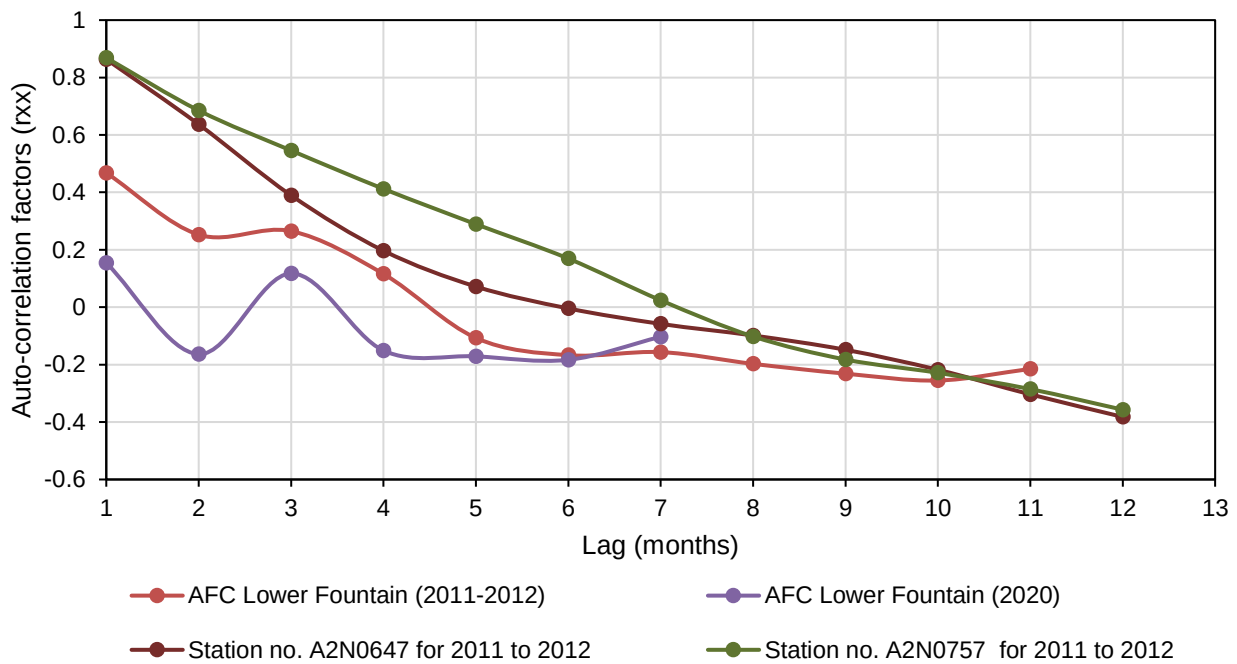


Figure 5-9: Auto-Correlation functions of spring discharge from the Lower Fountain Spring and water levels of the Fountain West Compartment for 2011 and 2012

5.6 WARMS QUERY OF REGISTERED BOREHOLES

A 10-kilometre desktop survey of the boreholes registered in the WARMS database was conducted. The desktop assessment was conducted to assess the density of boreholes within the Fountain West Karst Compartment relative to the Fountain East Karst Compartment. The locations of WARMS registered boreholes including the annual registered abstraction rates in m^3 are presented in Figure 5-10, with further details of each borehole presented in Appendix B.

The data from the WARMS database is considered important as it provides an indication of the spatial density and registered annual abstraction of boreholes of the study area. The spatial density and registered annual abstraction rates of the boreholes within the study area could possibly be influencing the discharge rates of the springs. It should be noted that these boreholes do not have long term groundwater level data and are rather registered groundwater abstraction points from public and private users.

The overall results indicate the presence of more registered groundwater abstraction points within the Fountain West Karst Compartment, relative to the Fountain East Compartment. The dominant groundwater use is irrigation followed by Schedule 1/domestic use (especially towards the southern portion of the study area). The highest registered groundwater

abstraction rates (i.e. $>176\,000\text{ m}^3/\text{year}$) are associated with the Grootfontein and Fountains springs and water supply boreholes (nine locations). The abstraction rates at the Grootfontein and Fountains springs were $353\,100\text{ m}^3/\text{year}$ and $12\,592\,500\text{ m}^3/\text{year}$ respectively, whilst abstraction rates greater than $176\,000\text{ m}^3$ are associated with borehole abstractions used for irrigation purposes as shown in Figure 5-10.

The assessment of registered groundwater abstractions within the Fountain East and West Karst Compartment highlighted a higher spatial distribution of boreholes within the Fountain West relative to the Fountain East. Higher abstractions are located along the southern portion of the Fountain West Karst Compartment, where a cone of depression would be expected. The higher borehole density within the Fountain West Karst Compartment, relative to the Fountain East Karst Compartment is likely affecting the volume of water discharged at the Lower Fountain Spring, relative to the Upper Fountain Spring as observed for spring discharge data from 2012, 2020 to 2021.

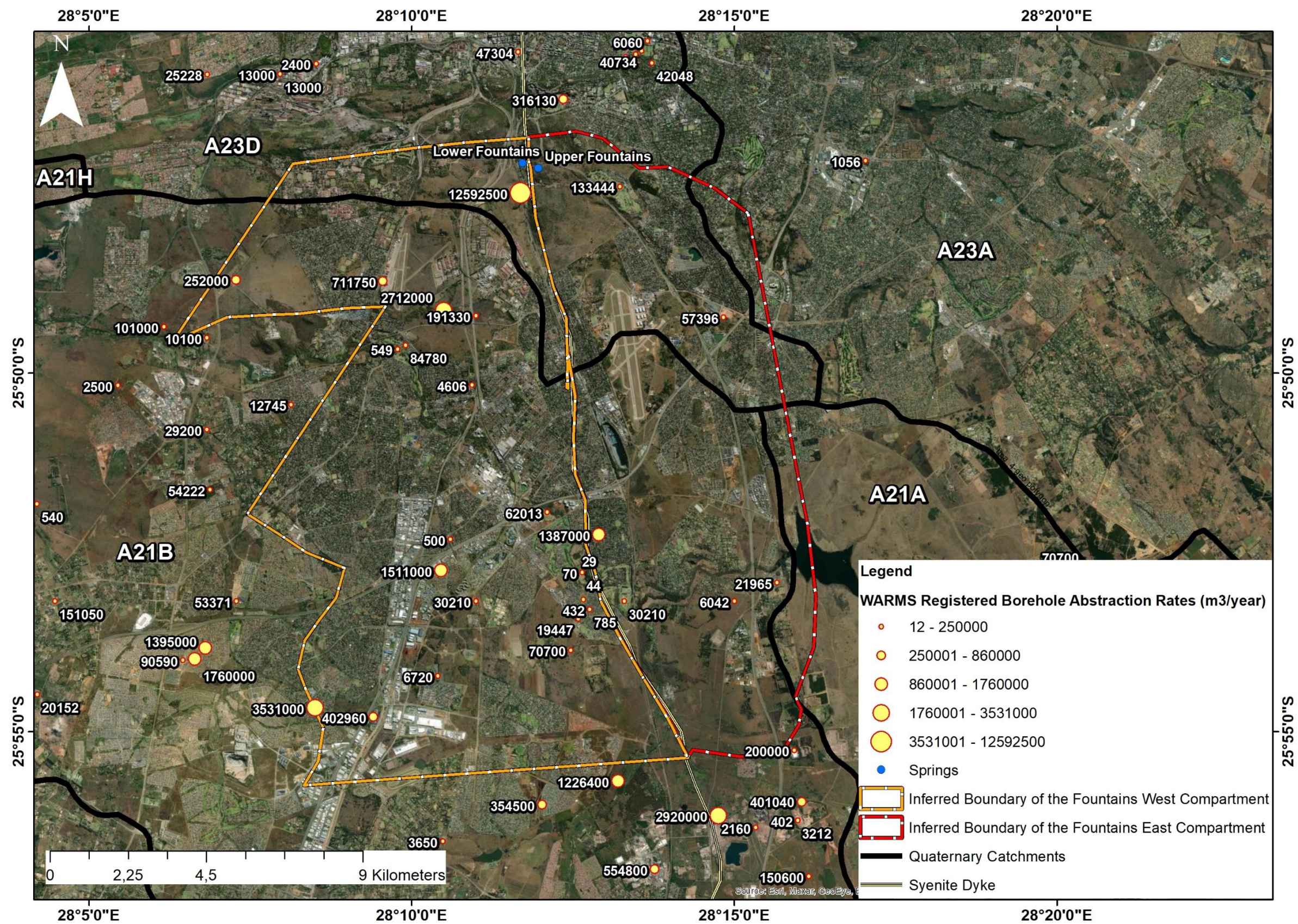


Figure 5-10: Map showing WARMS registered boreholes drilled into the Fountain West and East Karst Compartments

5.7 ASSESSMENT OF CHANGES IN LAND USE

A perusal of Google Earth Imagery® from 2008 to 2021 was done to identify areas of significant ground disturbance which could have acted as zones of artificial recharge. Surface disturbances can include open excavation (which would act as areas of artificial recharge) or new developments which would limit recharge to the aquifer but increase surface run-off.

The imagery from 2008 to 2021 are indicated below in Figure 5-11 to Figure 5-24. The Google Earth Imagery® from 2009, 2010, 2011 and 2012 indicates large ground disturbances along the Gautrain rail line on the Fountain West Karst Compartment and Waterkloof Airport, which started in 2009 since no ground disturbance was observed in 2008 except the open pit at Lyttelton Dolomite mine. Additional open excavations associated with gravel roads are observed immediately east of the Gautrain rail line and south of Waterkloof Airport during the same period as shown on the aerial imagery from 2011 and 2012 shown in Figure 5-14 and Figure 5-15.

The open excavation near the northern part of the Gautrain rail line is suspected to have resulted in artificial recharge near the Lower Fountain Spring between 2009 to 2012, especially where the dolomite was exposed to the surface whilst, the gravel roads are expected to be associated with increased run-off following compaction.

In 2019, 2020 and 2021 as shown in Figure 5-22 to Figure 5-24, open excavations were present in areas east of the Waterkloof Airport and above the Fountain East Karst Compartment. The open excavations include a man-made dam (northeast of Waterkloof Airport) and construction activities southeast of Waterkloof Airport. The man-made dam is expected to be associated with artificial recharge whilst areas of construction activities are expected to be associated with short term recharge and increased run-off once the area is fully developed.

Overall, the assessment was able to indicate the presence of significant ground disturbance near the Lower Fountain spring between 2009 to 2012 when compared to 2019, 2020 and 2021. Although spring discharge data for 2009 and 2010 was not available, it is considered unlikely that such erratic flows would have been caused by the ground disturbance along the Gautrain rail line and the erratic spring discharge data of the Lower Fountains is considered erroneous, especially since it has been reported by a CoT employee that the ultrasonic sensor/eye used to measure the water column in the rectangular weir can be inaccurate if the flow is too turbulent or the weir is flooded.



Figure 5-11: Map areas of potential artificial recharge to the karst compartments in 2008 (Blue arrows show areas of significant ground disturbance)

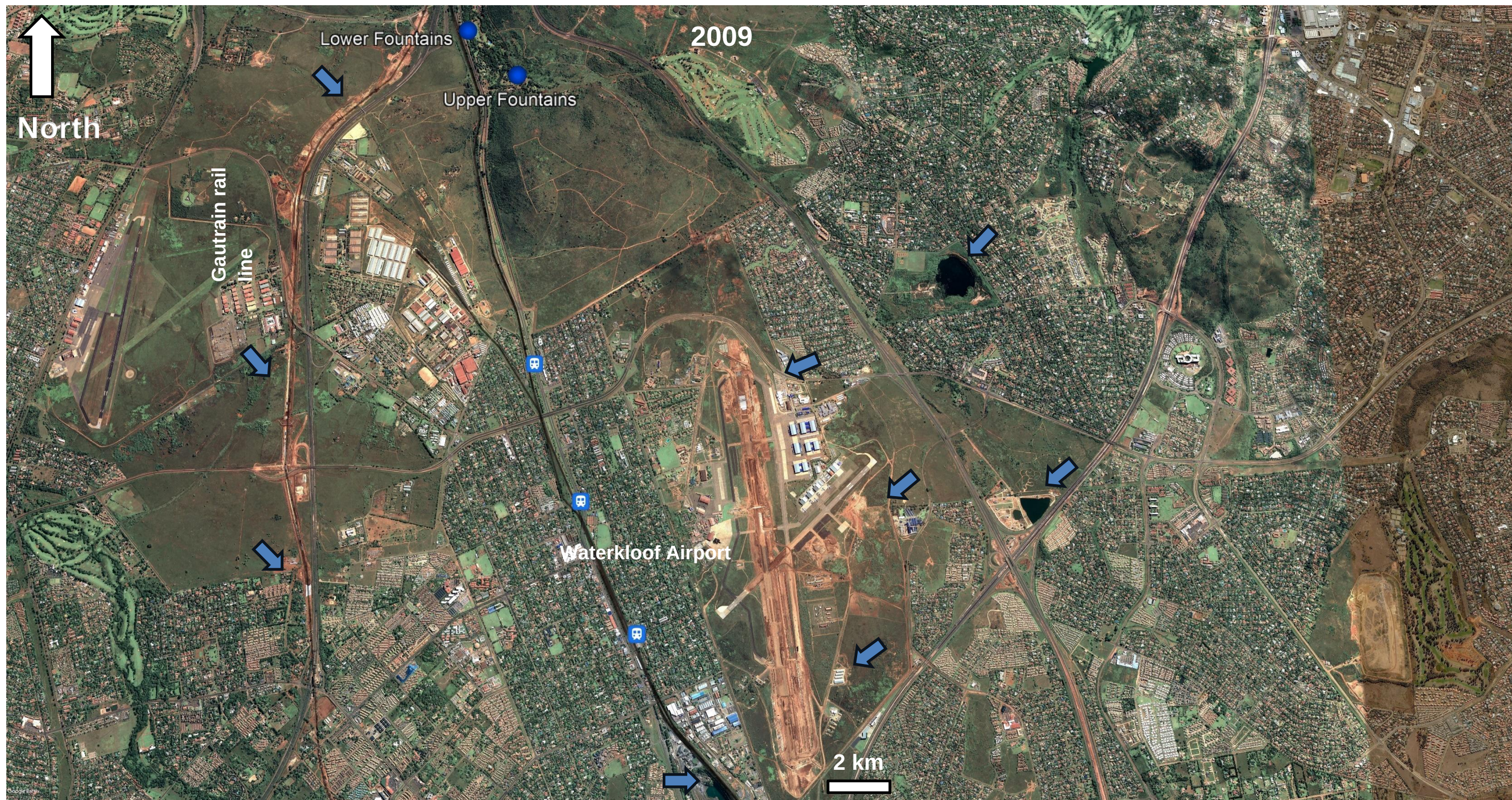


Figure 5-12: Map areas of potential artificial recharge to the karst compartments 2009 (Blue arrows show areas of significant ground disturbance)

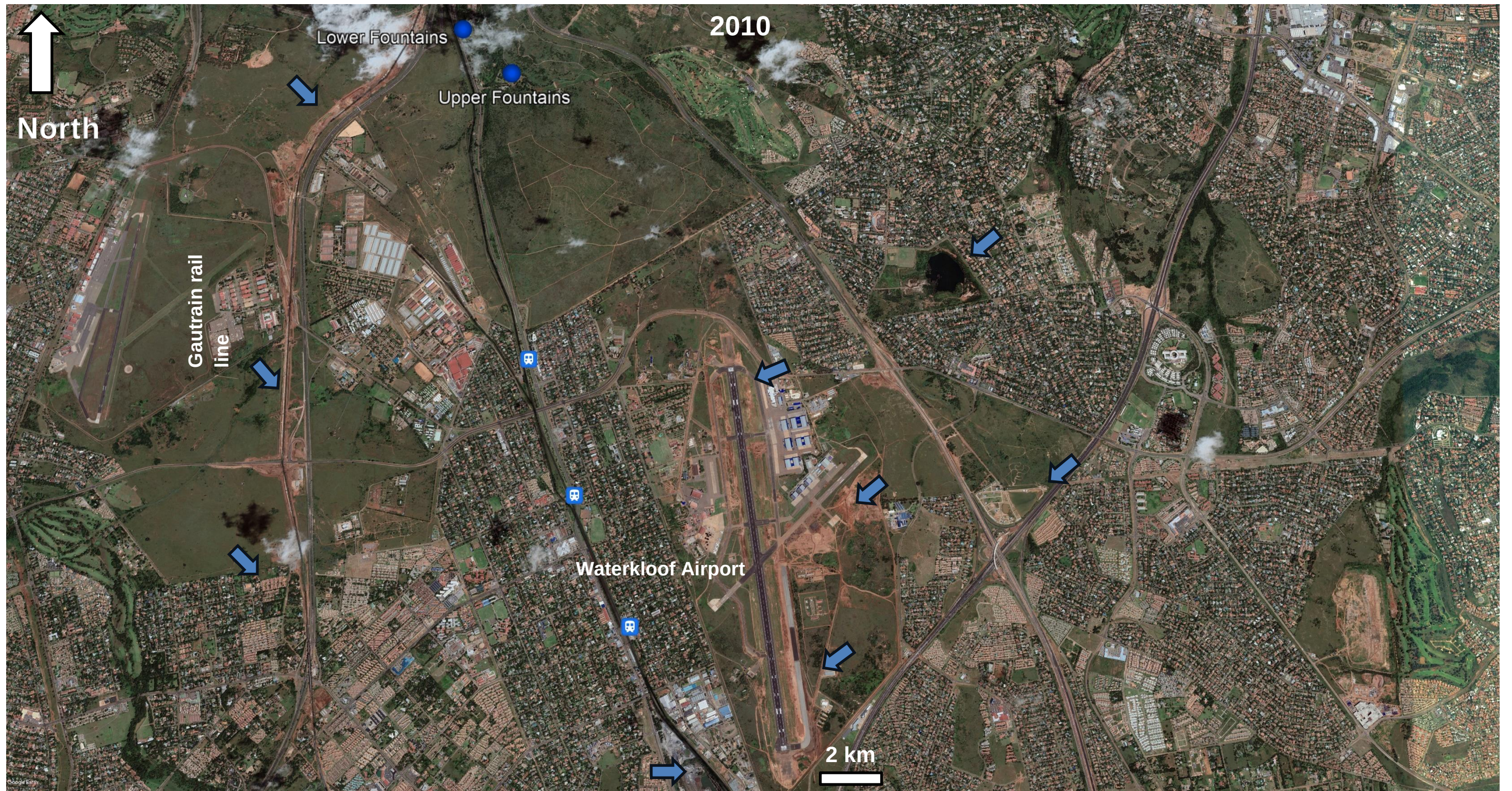


Figure 5-13: Map areas of potential artificial recharge to the karst compartments 2010 (Blue arrows show areas of significant ground disturbance)



Figure 5-14: Map areas of potential artificial recharge to the karst compartments 2011 (Blue arrows show areas of significant ground disturbance)



Figure 5-15: Map areas of potential artificial recharge to the karst compartments 2012 (Blue arrows show areas of significant ground disturbance)



Figure 5-16: Map areas of potential artificial recharge to the karst compartments 2013 (Blue arrows show areas of significant ground disturbance)

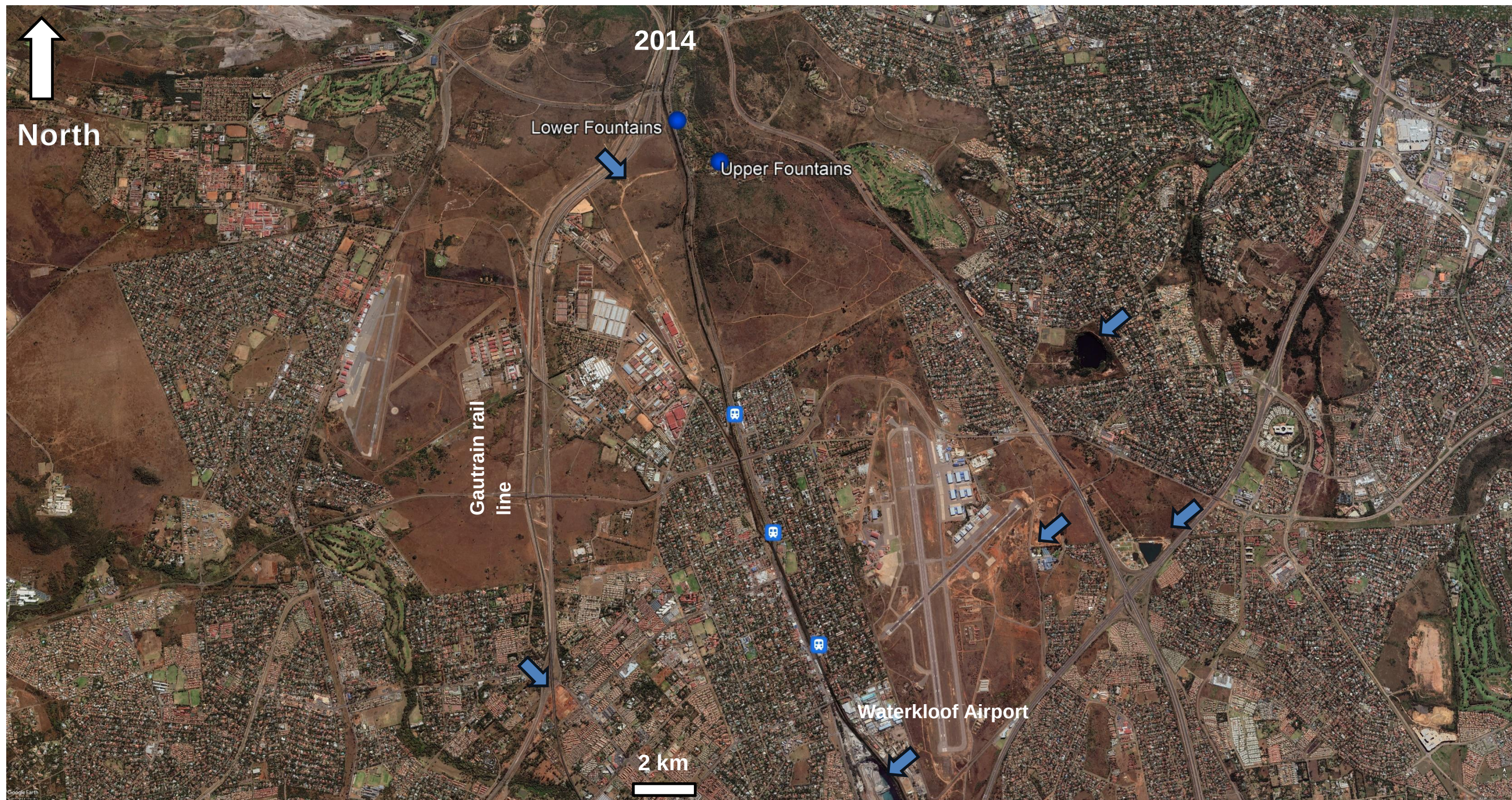


Figure 5-17: Map areas of potential artificial recharge to the karst compartments 2014 (Blue arrows show areas of significant ground disturbance)



Figure 5-18: Map areas of potential artificial recharge to the karst compartments 2015 (Blue arrows show areas of significant ground disturbance)



Figure 5-19: Map areas of potential artificial recharge to the karst compartments 2016 (Blue arrows show areas of significant ground disturbance)



Figure 5-20: Map areas of potential artificial recharge to the karst compartments 2017 (Blue arrows show areas of significant ground disturbance)



Figure 5-21: Map areas of potential artificial recharge to the karst compartments 2018 (Blue arrows show areas of significant ground disturbance)



Figure 5-22: Map areas of potential artificial recharge to the karst compartments 2019 (Blue arrows show areas of significant ground disturbance)



Figure 5-23: Map areas of potential artificial recharge to the karst compartments 2020 (Blue arrows show areas of significant ground disturbance)



Figure 5-24: Map areas of potential artificial recharge to the karst compartments 2021 (Blue arrows show areas of significant ground disturbance)

6 DISCUSSION

6.1 INTRODUCTION

This chapter provides a discussion of the results presented in Section 5, including the limitations of the selected methods and data used in this study. The chapter further presents an integration of the results of this study to develop a conceptual model of the Fountain East and West Karst Compartments which includes geological, hydrological, and hydrogeological data. The conceptual model provides information on the groundwater flow regimes within the karst compartments including information on how the karst compartments are recharged and discharged.

6.2 STRUCTURAL CONTROLS OF GROUNDWATER FLOW

The syenite dyke, geological faults, and sills of Pilanesberg age, are considered important structural controls for groundwater flow and chemistry of the dolomitic Fountain East and West Karst Compartments. The syenite dyke is a major geological structure compartmentalising the Fountain Karst Aquifer into the East and West Compartments, feeding the Upper and Lower Springs respectively. The E-W trending faults found within the study area are also considered important pathways of recharge to the compartments.

6.3 GROUNDWATER RECHARGE

The CCF assessment indicated evidence of allogenic recharge (recharge from afar) to the karst compartments. The Crocodile and Marico WMA where the karst compartments are located, receive 706 mm of rainfall per annum, of which 7 to 15% is recharge.

The effect of rainfall as assessed using CCF, was evidently delayed by 1 to 3 months before a response to water levels and spring discharge was observed. An increased effect of rainfall recharge was observed for CCF of the Fountain East Karst Compartment water levels against rainfall when compared to the Fountain West Karst Compartment.

The available Google Earth Imagery® indicated the presence of multiple surface water features (Rietvlei Dam, unnamed dams at Monument Park near Waterkloof Boulevard and

Erasmus Park, and the Lyttelton open pit mine) on the Fountain East Karst Compartment, considered secondary sources of recharge to the compartment.

The golf courses dominating the Fountain East Karst Compartment are also considered secondary sources of recharge where significant and consistent irrigation is occurring. The area on the Fountain West Karst Compartment has limited surface water features, considered to be sources of recharge except for an excavation clearly visible on Google Earth Imagery® from 2011 to 2012, considered a short-term secondary source of recharge. The Hennops River is also considered an important source of recharge to the Fountain West Karst Compartment.

6.4 GROUNDWATER DISCHARGE

The average spring discharge of the Lower Fountain was 25.81 ML/day between 2011 to 2012, and 97.17 ML/day between 2020 to 2021, whilst the average spring discharge of the Upper Fountain Spring was 22.28 ML/day in 2011 to 2012 and 102.13 ML/day in 2020 to 2021. Although the spring discharge of Lower Fountain seems higher than that of the Upper Fountain, it is considered that the smaller dimensions of the rectangular weir installed at the Lower Fountain could be cause of lower spring discharge relative to the Upper Fountain Spring.

The coefficient of recession suggests dominant flows within the Fountain East Karst Compartment have transitioned from a combination mixed and diffuse flows ($\alpha = 0.028$ to 0.006) between 2011 to 2012, to diffuse flow ($\alpha = 0.005$ to 0.004) in 2020 to 2021. The groundwater flow in the Fountain West Karst Compartment have transitioned from a combination of conduit to mixed flow ($\alpha = 0.531$ to 0.022) between 2011 to 2012, to diffuse flow ($\alpha = 0.001$ to 0.002) in 2020 and 2021.

It is apparent from the results of the AFC that the release of groundwater to the springs is not constant and could be influenced by localised recharge near the springs since CCF of rainfall and water levels were showing generally positive correlation when compared to CCF of rainfall and spring discharge data.

The desktop assessment of groundwater abstractions within the Fountain East and West Karst Compartment indicates a higher density of WARMS registered groundwater abstractions within the Fountain East Karst Compartment relative to the Fountain West Karst Compartment.

A cluster of Schedule 1 registered boreholes was observed south of the study area where the water table is deeper as indicated on the groundwater flow contour map, it is possible that the collective groundwater abstraction along the southern portion of the study area could be creating a cone of depression. The groundwater levels of some boreholes (A2N0637 and A2N0642) in the Fountain West Karst Compartment have been slightly erratic when compared to groundwater levels measured from boreholes in the Fountain East Karst Compartment as shown in Section 4.8.

6.5 GROUNDWATER FLOW WITHIN THE KARST COMPARTMENTS

The degree of karstification was assessed using the spring hydrographs and indicated possible disruption of groundwater flow within the Fountain East and West Karst Compartments between 2011 and 2012. The DKs computed from spring discharge data of 2011 and 2012 compared favourably with a complex system consisting of a highly karstified fabric and complex flow regimes (turbulent and laminar flows).

In contrast, the spring data from 2020 to 2021 indicate uninterrupted groundwater flow regimes, characterised by more laminar flow regimes, within a less karstified aquifer system. The higher DKs computed from 2011 to 2012 data could either be erroneous or indicate a disruption of groundwater flow of the karst compartments through intense artificial recharge (which is unlikely to cause the erratic flows observed in 2011).

The Fountain Karst Compartment are not considered intensely karstified, since the computed DKs for 2020 and 2021 were lower and compared favourably to karst aquifers dominated by laminar flow regimes. It is unlikely that the degree of karstification could change from highly karstified and revert back to less karstified in a short period of time, and therefore the spring discharge data from 2011 to 2012 is considered erroneous. In reality, the shift from higher DKs to lower DKs could mean that the epikarst contributed significantly to the overall in 2011 to 2012 when compared to 2020 and 2021 or the spring discharge data from 2011 to 2012 was erroneous.

The coefficient of recession commonly used in karst hydrogeology to assess the dominant flow of groundwater in karst aquifers, indicate conduit to mixed flow as dominant flows between 2011 and 2012, for both compartments. In 2020 and 2021, the dominant flow within the Fountain West Karst Compartment was mixed to diffuse, associated with flow from the fractures and the matrix whilst, in the Fountain East Karst Compartment, the dominant flow was mixed flow associated with fractures.

The results of the recession curve analyses corroborate the calculated degrees of karstification, indicating complex flow regimes between 2011 to 2012 where higher discharge rates are likely associated with conduit flow within the Fountains West Karst Compartment only, whilst lower to moderate discharge rates are likely associated with mixed and diffuse flow. It is apparent from the comparison of DKs and dominant flows between 2011 to 2012 and 2020 to 2021 that spring discharge rates have become stable between 2020 to 2021, where more diffuse flows were observed.

6.6 GROUNDWATER STORAGE WITHIN THE KARST COMPARTMENTS

The AFC is vital for determining the linear dependency water levels or spring flows. The linear dependency highlights the memory effect of a system and thus provides information on the storage capacity of the karst aquifers. Vegter (1986), estimated that the exploitable storage of the Fountain East Karst Compartment is between 4.5 to 7.5 Mm³ and, between 14 to 23 Mm³ for the Fountain West Karst Compartment.

The results of ACF indicated the presence of memory effect for water levels measured from the karst compartments, observed for up to 3 months, further providing evidence of significant storage within the karst compartments. A higher memory effect (indicative of higher groundwater storage capacity) was observed for water levels of the Fountain East Karst Compartment relative to the Fountain West Karst Compartment.

In contrast, the memory effect of spring discharge was very low, suggesting that the release of groundwater to the springs is erratic and not constant, the exception being the Lower Fountain Spring measured between 2011 to 2012, indicating the presence of a source of artificial recharge to the karst compartment.

6.7 GROUNDWATER FLOW CONCEPTUAL MODEL

The conceptual model of the Fountain East and West Karst Compartments is presented in Figure 6-1. The Fountain East and West Karst Compartments are formed by the Malmani dolomites of the Transvaal Supergroup and subdivided into five formations based on the abundance of chert within each formation. The amount of chert within each formation controls the degree of karstification which further controls the flow and storage of groundwater within each compartment.

The area where the Fountain East and West Karst Compartments are located is characterised by multiple dykes, sills, and faults of the Pilanesberg age, which control the movement of groundwater as described in detail by Naidoo (2014). The major geological structure is the North (N)-South (S) trending syenite dyke of the Pilanesberg age which has resulted in the compartmentalisation of the karst aquifer into the Fountain East and West Compartments as described by Holland and Wiegman (2009).

The N-S Syenite dyke and east-west trending shale ridge of the Timeball Hill Formation, north of the study area are considered major structures controlling the flow of groundwater within the study area, given that where the dolomites outcrop on surface within the Groenkloof Nature Reserve, two major springs emerge. These springs are called the Lower Fountain Spring, fed by the Fountain West Karst Compartment and the Upper Fountain Spring fed by the Fountain East Karst Compartment. Naidoo (2014) was able to show through hydrochemical characterisation that the water from the spring can be differentiated based on generally higher bicarbonate levels in the Upper Fountain Spring and generally higher cations and anions in the Lower Fountain Spring.

The recharge to the Fountain East and West Karst Compartments is of allogenic nature, meaning the compartments are recharged from afar, with headwaters located south of the study area.

A review of aerial imagery identified the presence of the Rietvlei Dam, multiple man-made surface water features and golf courses on the Fountain East Karst Compartments, which are considered secondary sources of recharge. The Gautrain and Metrorail lines are notably on the Fountain West Karst Compartment, and these are considered potential areas of both recharge (where the dolomites have been exposed during construction) and discharge (where dewatering is practiced) areas.

The water from the springs is vital in supporting the ecosystem of the Apies River and augmenting the drinking water supply of the City of Tshwane, which relies on ~57 Ml/day (7.7%) of groundwater to meet drinking water demands. The mean annual precipitation of the study area is 706 mm/annum of which 7 to 15% becomes recharge to the groundwater. The springs are therefore considered natural discharge zones of the compartments.

A review of WARMS database which does not have long term groundwater monitoring data, indicated the presence of multiple boreholes within the compartments. The highest number of boreholes with higher annual abstractions are evidently within the Fountain West Karst Compartment.

The Lyttelton dolomite mine is located 6 km south, and up-hydraulic gradient of the study area, within the Fountain East Karst Compartment and is considered a point of discharge (during dewatering) and recharge (when the pit is filled with water following heavy rains) to the compartment. A cluster of Schedule 1 (domestic use) registered boreholes south of the study area is considered to create a cone of depression, resulting in the water table being deeper in the area.

In addition to the geological structures (dykes and faults), dissolution features and the matrix of the dolomites are considered vital in controlling the distribution of recharge and, flow and storage of groundwater. The flow of groundwater within the Fountain West Karst Compartment is considered to be single laminar flow, where dominant flow regimes are mixed to diffuse (i.e. fracture and conduit controlled). Similarly, the flow of groundwater within the Fountain East Karst Compartment is laminar, where dominant flow regimes are mixed (fracture and conduit).

It is considered likely that the presence of more surface water features such as dams and golf courses within the Fountain East Karst Compartment including the Hennops River on the Fountain West Karst Compartment play a significant role of replenishing the aquifer at varying recharge rates and thus possibly resulting in mixed flow regimes.

The results of auto-correlation considered important for determining the memory effect/storage capacity of karst aquifers indicate a higher groundwater storage capacity within the Fountain East when compared to the Fountain West Karst Compartments. However, the linear dependency of spring discharge was observed to be very poor, indicating that the release of groundwater to the springs is inconsistent on a smaller scale, the exception being the spring discharge data from 2011 to 2012 collected from the Lower Fountain Spring, possibly indicating erroneous data or increased recharge near the spring, responsible for higher baseflow contribution to the shallow groundwater.

Naidoo (2014) suggested that there could have been a source of erratic flow within the Lower Fountain Spring when compared to the Upper Fountain Spring, the results of the auto-correlation assessment indicate the presence of memory effect for the spring discharge data of the Lower Fountain Spring discharge from 2011 to 2012, likely due to increase recharge near the spring as a results of ground disturbance. The spring hydrographs from 2020 to 2021 indicate relatively stable spring discharges for the Lower and Upper Fountain Springs.

In summary, the available geological and hydrogeological data of the Fountain East and West Karst Compartments, was collated, and statistically analysed to assess whether there is evidence of erratic spring discharge within the Lower Fountain Spring associated with Fountain West Karst Compartment.

The data suggest that although the groundwater flow regimes within the Fountain East and West Karst Compartments are varying, there is no long-term evidence of erratic spring discharge within the Lower Fountain Spring when compared to the Upper Fountain Spring. The higher spring discharge data measured between July and November 2011 is considered erroneous or a result of increased recharge near the spring especially (considered unlikely to have such an effect), since the data from 2016 to 2021, as indicated in Figure 4-18 indicates similar spring discharge rates for the Upper and Lower Fountain Springs.

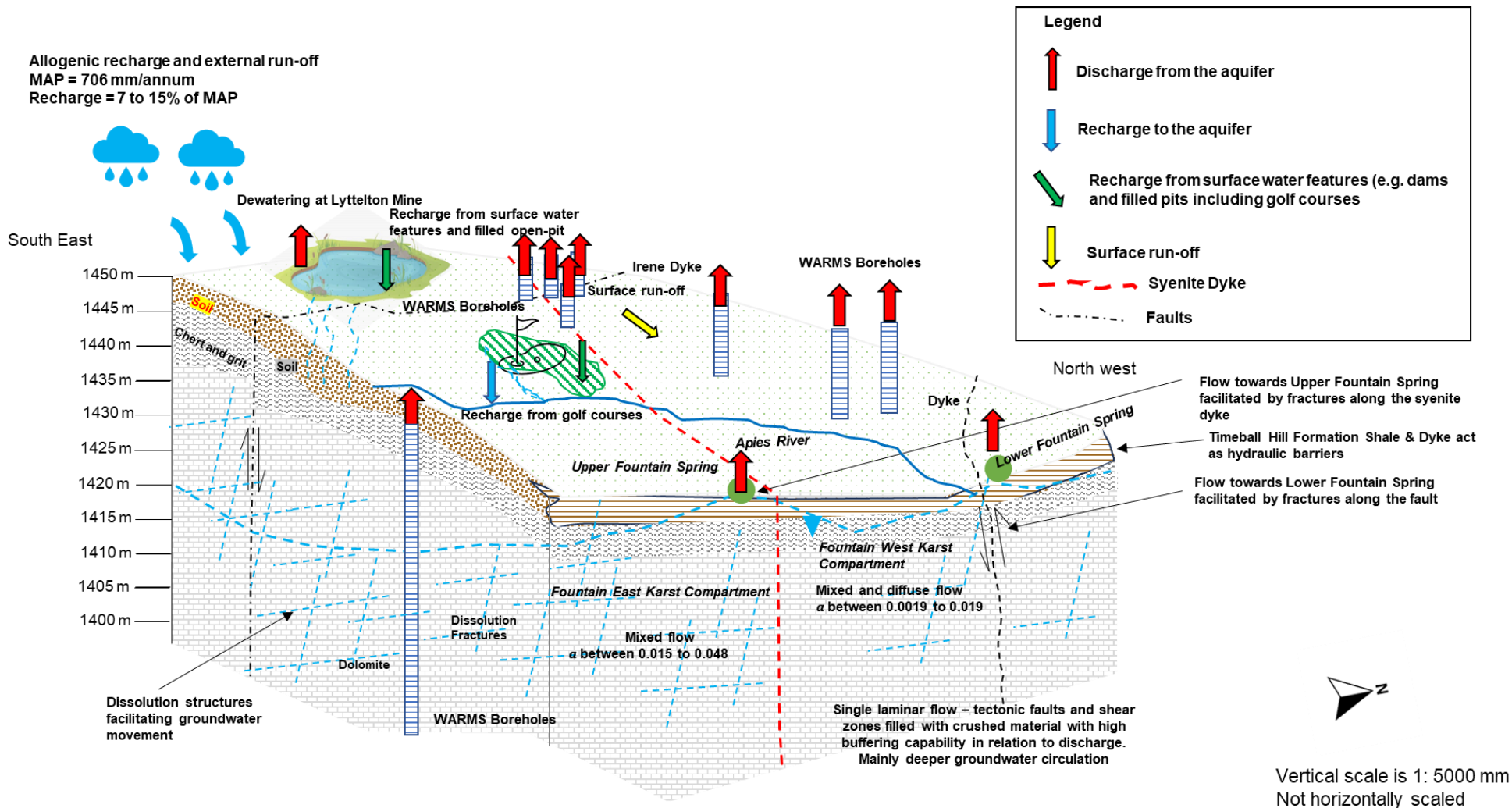


Figure 6-1: Southeast to northwest conceptual hydrogeological model of the study area showing groundwater recharge and discharge points, dominant flow within the Fountain East and West Karst Compartment

6.8 LIMITATIONS OF THE STUDY

The spring discharge data received from the CoT was not continuous (i.e. between 2011 to 2021), resulting in limited data available for hydrograph analyses, ACF and CCF analyses. The groundwater data was mostly continuous up to 2020 and 2021 data collection was disrupted by travel restrictions associated the COVID pandemic.

The use of ACF and CCF is considered a common practice in the field of karst hydrology for assessing the effect of rainfall to the karst aquifer and storage capacity of karst aquifers respectively, and the accuracy of these methods increases when long-term continuous data is used. The assessment of spring hydrographs was limited by the available data which is considered limited, and the accuracy of spring hydrographs also increases when long-term continuous data is available. The calculated DKs and recession coefficients could be refined as continuous long-term data is collected in the future.

The procedure of assessing the accuracy of the spring discharge data is not well documented and for this study, rainfall was used as a tool to assess the reliability of the spring discharge data, and the rainfall patterns conformed well with spring discharge data, especially spring discharge data collected from 2016 onwards. The study conducted by Meyer (2014), further highlighted that the groundwater quantity within the Fountain Karst Compartments was increasing over time. The accuracy of DKs is reliant on the amount of data available, where a hydrograph with more datasets provides more accurate DKs than hydrographs with less dataset.

CONCLUSIONS AND RECOMMENDATIONS

A summary of the conclusions and recommendations from the study are presented in the subsections below.

7.1 CONCLUSIONS

The study assessed the groundwater flow regimes of the Fountain East and West Karst Compartments to confirm the potential cause of erratic spring flows in the Lower Fountain Spring, as indicated by Naidoo (2014). The available geological data indicate that the north-south trending syenite dyke and east-west shale ridge north of the study area, are primary geological structures controlling the flow of groundwater through the Fountain Karst Compartments to the Fountain Springs. The results of cross correlation function suggest the Fountain Karst Compartments are recharged from afar (allogenic recharge) since the effect of rainfall on groundwater levels is observed after ~3 months. The headwaters responsible for recharge to the Fountain Karst Compartments are considered to be south of the study area.

The degree of karstification determined from spring hydrograph data from 2011 to 2012 indicate complex flows of turbulent to laminar nature within a highly karstified environment whilst, degree of karstification determined from spring hydrograph data from 2020 to 2021 indicate less complex laminar flow within a less karstified environment. It is considered geologically unlikely that the degree of karstification can transition from highly karstified to less karstified and, the spring discharge from 2011 to 2012 is considered erroneous, especially since it has been reported by a CoT employee, that the ultrasonic sensors used to measure changes in head/water column within the rectangular weirs are sensitive to turbulent flows. In reality, the shift from higher DKs to lower DKs could mean that the epikarst contributed significantly to the overall in 2011 to 2012 when compared to 2020 and 2021 or the spring discharge data from 2011 to 2012 was erroneous. Historical aerial imagery indicates extensive ground disturbance near the spring between 2009 and 2012 but it is considered unlikely that artificial recharge could be a source of the erratic spring discharge observed in 2011.

The recession coefficients determined from the spring hydrographs of 2011 to 2012, indicate that groundwater flow from the Fountain West Karst Compartment to the Lower Fountain Spring was from conduits during peak flows, and a combination of fractures and matrix (i.e. mixed flow) during baseflow. In the Fountain East Karst Compartment, the recession coefficients calculated from 2011 to 2012 spring hydrographs, indicated release of groundwater from the matrix and fractures during peak flows and the matrix only through diffuse flow, during baseflow.

The recession coefficients from the spring hydrographs of 2020 to 2021, considered more accurate, indicate that the release of groundwater from the Fountain West Karst Compartment to the Lower Fountain Spring was of diffuse nature (release from the matrix) associated with laminar flows during peak flow to diffuse flow (release from the matrix with more laminar flow during baseflow. Similar to the Fountain West Karst Compartment, the flow of groundwater to the springs is considered stable and, dominated by mixed flows, associated with the release of groundwater from the matrix/laminar flow and fractures/turbulent.

A higher spatial distribution of WARMS registered Schedule 1 (domestic use) groundwater abstractions is noted within the Fountain West Karst Compartment relative to the Fountain East Karst Compartment. The highest number of registered groundwater abstractions are found within the Fountain West Karst Compartment relative to the Fountain East Karst Compartment. The higher density of boreholes used for irrigation purposes along the southern part of Fountain West Karst Compartment, is considered to result in a localised cone of depression as indicated by a deeper water table in the area. The abstraction of groundwater at Lyttelton Dolomite Mine, located at the same area could be another source resulting in a cone of depression during dewatering activities.

The objectives of the study were met, and the updated conceptual model was able to indicate the areas of groundwater abstraction and recharge, including geological structures responsible for the storage and flow of groundwater to the Upper and Lower Fountains Springs. The updated conceptual model is considered useful for future research or work where an understanding of groundwater flow mechanisms and major controls of flow within the Fountains East and West Karst Compartments is required. The study is considered to have provided an important contribution to society, as it addresses SDG6 (clean water and sanitation) and SDG15 (life on land) of the United Nations' Sustainable Development Goals given that an understanding of flow mechanisms of the Fountains will assist the City of

Tshwane to better manage the water resource and put additional measures to protect the ecosystem of the Apies River where needed.

7.2 RECOMMENDATIONS

The following are recommended to gain more understanding of the flow regimes within the Fountain Karst Compartment and ensure spring discharge data is shared with the DWS:

- The Department of Water and Sanitation (DWS) should consider being the custodian of spring discharge data from the Lower and Upper Fountain Springs Discharge in line with the DWAF *“Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa”* (2008).
- Local rainfall data near the springs should be considered for future studies to assess the effect of autogenic recharge to the discharge of the Fountain Springs.
- The CoT should consider installing a weir with similar dimensions to the Upper Fountain Spring at the outlet of the Lower Fountain Spring to ensure measured spring discharge is more representative.
- The water level on the stick gauge should be measured concurrently with spring discharge data from the electronic gauge and use to validate the measure spring discharge, especially when discharge is highly turbulent.

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ABSTRACT

The flow of groundwater within the Fountain East and West Karst Compartments feeding the Upper and Lower Fountain was studied to assess the potential cause of erratic flow to the Lower Fountain Spring. Statistical and graphical methods comprising cross correlation, auto correlation, degree of karstification and recession curve analyses were used to assess the flow mechanisms of the aquifer. The syenite dyke of Pilanesberg age and shale of the Timeball Hill Formation north of the study area, are the primary controls of varying hydrochemistry and flow within the dolomitic Fountain East and West Karst Compartments towards the Lower and Upper Fountain Springs. The available spring discharge data indicates an overall increase in the discharges of both springs from 25.81 Ml/day to 97.17 Ml/day for the Lower Fountain Spring and 22.28 Ml/day to 102.13 Ml/day between 2011 to 2021, for the Upper Fountain Spring. The increase in spring discharges is consistent with changes in rainfall patterns and the results of cross-correlation function indicate a delayed response to the groundwater levels and spring discharge, ranging from 1 month to 3 months. The delayed response provides evidence of allogenic recharge to the karst compartments.

The auto-correlation function, useful for assessing linear dependency between successive data points, indicated the presence of memory effect in groundwater levels within the Fountain East and West Karst Compartments. Auto-correlation assessment further suggests the Fountain East Karst Compartment has a higher groundwater storage capacity than the Fountain West Karst Compartment. The presence of memory effect in the compartments was observed to be up to 3 months, providing evidence of increased storage within the compartments. In contrast, the memory effect of spring discharge was very low suggesting that the release of groundwater to the springs is erratic and not constant, the exception being Lower Fountain Spring discharge from 2011 to 2012, indicating the presence of a sustained source of recharge near the spring. Although the calculated degrees of karstification indicate higher karstification in 2010 to 2011 compared to 2020 and 2021, it is likely that the Lower Fountain Spring discharge data is erroneous, especially since the City of Tshwane (CoT) indicated that the ultrasonic sensor used to measure changes in head within the rectangular weir is sensitive to turbulent flows. The calculated coefficients of recession for the Fountain East Compartment were between 0.005 to 0.028 in 2011 and 2012 and, 0.004 to 0.005 in 2020 and 2021, indicating a transition from mixed flow to predominant diffuse flow. The calculated coefficients of recession for the Fountain West Compartment were between 0.022 to 0.531 in 2011 and 2012, and 0.001 to 0.002 in 2020 and 2021, indicating a transition from conduit to diffuse flows.

APPENDIX A: SPRING DISCHARGE DATA (2011-2012 AND 2020-2021)

TABLE A1 – SPRING DISCHARGE DATA FROM 2011 TO 2021

Month	Upper Fountain (MI/day)	Lower Fountain (MI/day)
Jul-11	23.27	58.69
Aug-11	23.21	22.46
Sep-11	22.88	45.88
Oct-11	22.51	64.40
Nov-11	19.09	42.12
Dec-11	23.72	15.50
Jan-12	19.62	13.11
Feb-12	26.38	18.07
Mar-12	22.59	15.68
Apr-12	22.57	15.48
May-12	22.21	15.32
Jun-12	21.79	14.98
Jul-12	21.46	15.07
Aug-12	21.13	14.95
Sep-12	21.81	15.51
Jul-16	78.81	85.03
Jul-16	79.14	85.27
Aug-16	79.69	85.69
Oct-16	80.58	86.4
Feb-18	94.79	94.55
Mar-18	88.66	91.69
Aug-18	88.91	91.80
Aug-18	87.88	91.33
Sep-18	89.16	91.91
Sep-18	89.64	92.13
Oct-18	90.17	92.38
Feb-19	94.79	94.55
Sep-19	98.46	95.85
Nov-19	100.96	96.74
Jan-20	104.86	98.15
Feb-20	105.46	98.39
Mar-20	100.44	96.57
Apr-20	101.45	97.07
May-20	101.98	97.33
Sep-20	100.51	96.6
Sep-20	101.33	97.07
Oct-20	102.91	96.89
Feb-21	100.27	96.49
Apr-21	100.26	96.5
May-21	100.27	96.5
Aug-21	101.62	96.72
Sep-21	101.95	96.94
Sep-21	101.95	96.99
Sep-21	100.27	96.49
Oct-21	100.31	96.53

APPENDIX B: ABSTRACTION AND GROUDNWATER USE OF WARMS REGISTERED BOREHOLES

TABLE B1 – GEOGRAPHIC COORDINATES, GROUNDWATER USE AND REGISTERED ABSTRACTIONS OF WARMS BOREHOLES

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26007838	-25.9383	28.3897	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	17471
26009499	-25.8515	28.0456	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	4380
26013778	-25.9849	28.3311	SPRING/EYE	AGRICULTURE: IRRIGATION	65137
26014385	-25.8362	28.0907	BOREHOLE	AGRICULTURE: IRRIGATION	2500
26014893	-25.9609	28.3005	BOREHOLE	AGRICULTURE: IRRIGATION	119463
26015730	-26.0559	28.3512	BOREHOLE	AGRICULTURE: IRRIGATION	1084
26021420	-25.9389	28.25556	BOREHOLE	INDUSTRY (URBAN)	2160
26022483	-25.925	28.3351	BOREHOLE	INDUSTRY (URBAN)	7489.9
26023231	-25.7839	28.28389	BOREHOLE	AGRICULTURE: IRRIGATION	1056
26024098	-25.9372	28.26639	BOREHOLE	INDUSTRY (URBAN)	3212
26024150	-25.8944	28.03889	BOREHOLE	MINING	4800
26024187	-25.9935	28.374	BOREHOLE	AGRICULTURE: IRRIGATION	8170
26024285	-25.9013	28.0555	BOREHOLE	AGRICULTURE: IRRIGATION	8522
26024338	-25.7899	28.2205	BOREHOLE	AGRICULTURE: IRRIGATION	133444
26025756	-25.9045	28.0597	BOREHOLE	AGRICULTURE: IRRIGATION	208
26026121	-25.9426	28.4279	BOREHOLE	AGRICULTURE: IRRIGATION	20150
26026979	-25.9767	28.1299	BOREHOLE	AGRICULTURE: IRRIGATION	7774
26029976	-25.4991	28.0814	BOREHOLE	AGRICULTURE: IRRIGATION	12500
26030697	-25.9118	28.4149	BOREHOLE	AGRICULTURE: IRRIGATION	11572
26033248	-25.9111	28.14167	SPRING/EYE	SCHEDULE 1	3531000
26033248	-25.8863	28.0744	BOREHOLE	AGRICULTURE: IRRIGATION	151050
26033248	-25.8863	28.2216	BOREHOLE	AGRICULTURE: IRRIGATION	30210
26033248	-25.9361	28.24583	SPRING/EYE	SCHEDULE 1	2920000
26033248	-25.8792	28.1742	BOREHOLE	SCHEDULE 1	1511000
26033328	-25.8882	28.2126	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	785
26033328	-25.8882	28.2126	BOREHOLE	SCHEDULE 1	58272

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26033480	-25.9147	28.0537	BOREHOLE	SCHEDULE 1	18720
26033890	-25.8637	28.0698	BOREHOLE	AGRICULTURE: AQUACULTURE	540
26041685	-25.7511	28.1046	BOREHOLE	INDUSTRY (URBAN)	7020
26044744	-25.8882	28.2126	BOREHOLE	INDUSTRY (URBAN)	7300
26044744	-25.8796	28.2107	BOREHOLE	AGRICULTURE: IRRIGATION	17836
26044744	-25.8796	28.2107	BOREHOLE	SCHEDULE 1	172
26044753	-25.8796	28.2107	BOREHOLE	SCHEDULE 1	29
26044762	-25.8796	28.2107	BOREHOLE	SCHEDULE 1	44
26046644	-25.9841	28.4153	BOREHOLE	AGRICULTURE: IRRIGATION	562297
26046671	-25.977	28.406	BOREHOLE	AGRICULTURE: IRRIGATION	72960
26051067	-25.9709	28.3107	SPRING/EYE	AGRICULTURE: IRRIGATION	175200
26051236	-26.0236	28.4242	BOREHOLE	AGRICULTURE: IRRIGATION	570940
26051469	-25.8977	28.2077	BOREHOLE	AGRICULTURE: IRRIGATION	70700
26053378	-25.9662	28.3295	BOREHOLE	AGRICULTURE: IRRIGATION	26067
26054108	-25.9793	28.3919	BOREHOLE	AGRICULTURE: IRRIGATION	248274
26054180	-25.8847	28.04201	BOREHOLE	INDUSTRY (NON-URBAN)	28382
26054180	-25.8753	28.0466	BOREHOLE	INDUSTRY (NON-URBAN)	1104
26054938	-26.0958	28.2831	BOREHOLE	AGRICULTURE: IRRIGATION	24455
26054956	-25.9901	28.177	BOREHOLE	AGRICULTURE: IRRIGATION	276500
26055508	-25.9	28.1075	BOREHOLE	AGRICULTURE: IRRIGATION	90590
26059121	-25.9647	28.233	BOREHOLE	AGRICULTURE: IRRIGATION	373380
26061644	-25.8225	28.1026	BOREHOLE	AGRICULTURE: IRRIGATION	101000
26064927	-25.975	28.3406	BOREHOLE	AGRICULTURE: IRRIGATION	103530
26064954	-25.9789	28.3538	BOREHOLE	AGRICULTURE: IRRIGATION	83265
26064981	-25.9758	28.3441	BOREHOLE	AGRICULTURE: IRRIGATION	125677
26065007	-25.9742	28.356	BOREHOLE	AGRICULTURE: IRRIGATION	10950
26065285	-25.8032	28.0128	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	147825

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26065356	-25.9999	28.3338	BOREHOLE	AGRICULTURE: IRRIGATION	51503
26065409	-25.8421	28.05734	BOREHOLE	INDUSTRY (URBAN)	54750
26066408	-25.9841	28.41688	BOREHOLE	INDUSTRY (NON-URBAN)	13726
26066408	-25.986	28.4224	BOREHOLE	AGRICULTURE: IRRIGATION	34332
26069067	-25.9643	28.2588	BOREHOLE	INDUSTRY (NON-URBAN)	3600
26069192	-25.908	28.06989	BOREHOLE	AGRICULTURE: IRRIGATION	20152
26069272	-25.9209	28.2655	BOREHOLE	INDUSTRY (URBAN)	200000
26070518	-25.9933	28.3677	BOREHOLE	AGRICULTURE: IRRIGATION	33380
26070625	-25.8904	28.2097	BOREHOLE	AGRICULTURE: IRRIGATION	19447
26070670	-25.8859	28.211	BOREHOLE	AGRICULTURE: IRRIGATION	49915
26070821	-25.8968	28.3645	BOREHOLE	AGRICULTURE: IRRIGATION	326452
26070929	-25.9907	28.3704	BOREHOLE	AGRICULTURE: IRRIGATION	233669
26075283	-25.9997	28.24075	BOREHOLE	INDUSTRY (URBAN)	15768
26077600	-25.9421	28.17467	BOREHOLE	SCHEDULE 1	3650
26078636	-26.0929	28.27106	BOREHOLE	INDUSTRY (URBAN)	5475
26078930	-26.0545	28.25015	BOREHOLE	MINING	25125
26079680	-25.9621	28.14269	BOREHOLE	AGRICULTURE: IRRIGATION	12000
26079957	-26.008	28.25215	BOREHOLE	INDUSTRY (URBAN)	12
26080044	-25.7532	28.22522	BOREHOLE	AGRICULTURE: IRRIGATION	54556.55
26080099	-25.7591	28.2245	BOREHOLE	AGRICULTURE: IRRIGATION	56502
26080810	-25.9542	28.3564	BOREHOLE	AGRICULTURE: IRRIGATION	1825
26081070	-25.8464	28.1137	BOREHOLE	INDUSTRY (URBAN)	29200
26081141	-25.9674	28.22722	BOREHOLE	INDUSTRY (URBAN)	315360
26083425	-26.0418	28.30825	BOREHOLE	AGRICULTURE: IRRIGATION	121804
26083498	-25.9281	28.21995	BOREHOLE	INDUSTRY (URBAN)	1226400
26007589	-25.9411	28.3905	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	87353
26009499	-25.8515	28.0456	BOREHOLE	AGRICULTURE: IRRIGATION	121200
26011431	-26.0562	28.2818	BOREHOLE	AGRICULTURE: IRRIGATION	33616
26014321	-25.9043	28.0654	BOREHOLE	AGRICULTURE: IRRIGATION	10000

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26019905	-25.8788	28.3287	BOREHOLE	AGRICULTURE: IRRIGATION	70700
26024098	-25.9329	28.26739	BOREHOLE	MINING	401040
26024098	-25.9372	28.26639	BOREHOLE	MINING	401.5
26024150	-25.8944	28.03889	BOREHOLE	INDUSTRY (URBAN)	7200
26024472	-25.9484	28.4436	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	25000
26025756	-25.9072	28.0584	BOREHOLE	INDUSTRY (NON-URBAN)	17720
26026951	-25.7561	28.2276	BOREHOLE	AGRICULTURE: IRRIGATION	6060
26027095	-25.5472	28.1152	BOREHOLE	AGRICULTURE: IRRIGATION	17500
26030189	-25.9937	28.4485	BOREHOLE	AGRICULTURE: IRRIGATION	12260
26030615	-25.8277	28.163	BOREHOLE	AGRICULTURE: IRRIGATION	549
26030704	-25.9111	28.4158	BOREHOLE	AGRICULTURE: IRRIGATION	5786
26033248	-25.8708	28.215	BOREHOLE	SCHEDULE 1	1387000
26033248	-25.8863	28.1832	BOREHOLE	AGRICULTURE: IRRIGATION	30210
26033248	-25.82	28.1832	BOREHOLE	AGRICULTURE: IRRIGATION	191330
26033248	-25.8188	28.1749	BOREHOLE	WATER SUPPLY SERVICE	2712000
26033248	-25.8972	28.11333	BOREHOLE	SCHEDULE 1	1395000
26033300	-25.8796	28.2107	BOREHOLE	INDUSTRY (URBAN)	206170
26033328	-25.8796	28.2107	BOREHOLE	INDUSTRY (URBAN)	488
26033854	-25.8604	28.1145	BOREHOLE	AGRICULTURE: IRRIGATION	54222
26034103	-25.9623	28.391	BOREHOLE	AGRICULTURE: IRRIGATION	51730
26037654	-25.9639	28.4264	BOREHOLE	AGRICULTURE: IRRIGATION	50500
26038136	-25.9132	28.1567	BOREHOLE	AGRICULTURE: IRRIGATION	402960
26041685	-25.7511	28.1046	BOREHOLE	INDUSTRY (URBAN)	600
26041685	-25.7511	28.1046	BOREHOLE	INDUSTRY (URBAN)	3660
26044548	-25.9834	28.3048	BOREHOLE	INDUSTRY (URBAN)	55000
26044744	-25.8882	28.2126	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	432
26044744	-25.8882	28.2126	BOREHOLE	AGRICULTURE: IRRIGATION	50698
26044744	-25.8796	28.2107	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	70

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26044744	-25.8882	28.2126	BOREHOLE	SCHEDULE 1	32877
26044753	-25.8882	28.2126	BOREHOLE	SCHEDULE 1	5613
26044762	-25.8882	28.2126	BOREHOLE	SCHEDULE 1	8374
26046635	-25.981	28.4139	BOREHOLE	AGRICULTURE: IRRIGATION	41826
26046653	-25.9864	28.4159	BOREHOLE	AGRICULTURE: IRRIGATION	718202
26046671	-25.977	28.406	BOREHOLE	AGRICULTURE: IRRIGATION	33290
26047162	-25.8723	28.0259	BOREHOLE	AGRICULTURE: IRRIGATION	8960
26048269	-25.9694	28.4303	BOREHOLE	AGRICULTURE: IRRIGATION	15821
26051067	-25.9709	28.3107	BOREHOLE	AGRICULTURE: IRRIGATION	2000
26051192	-26.0817	28.3201	BOREHOLE	INDUSTRY (URBAN)	3285
26051370	-25.9204	28.31283	BOREHOLE	AGRICULTURE: IRRIGATION	109500
26053378	-25.9656	28.3346	BOREHOLE	AGRICULTURE: IRRIGATION	70267
26054064	-25.7638	28.1326	BOREHOLE	INDUSTRY (NON-URBAN)	13000
26054117	-25.9758	28.3927	BOREHOLE	AGRICULTURE: IRRIGATION	259227
26054180	-25.8854	28.05049	BOREHOLE	AGRICULTURE: IRRIGATION	43196
26054180	-25.8666	28.05419	BOREHOLE	INDUSTRY (NON-URBAN)	31536
26054938	-26.0958	28.2831	BOREHOLE	INDUSTRY (URBAN)	6935
26059274	-26.9114	28.06189	BOREHOLE	AGRICULTURE: IRRIGATION	73000
26059808	-26.0153	28.43403	BOREHOLE	WATER SUPPLY SERVICE	60000
26063624	-25.7613	28.14192	BOREHOLE	INDUSTRY (URBAN)	2400
26064936	-25.9759	28.3516	BOREHOLE	AGRICULTURE: IRRIGATION	107451
26064963	-25.9814	28.3515	BOREHOLE	AGRICULTURE: IRRIGATION	135846
26064990	-25.9826	28.3424	BOREHOLE	AGRICULTURE: IRRIGATION	408283
26065016	-25.9777	28.3579	BOREHOLE	AGRICULTURE: IRRIGATION	107803
26065105	-25.9897	28.36258	BOREHOLE	AGRICULTURE: IRRIGATION	151506
26065356	-25.9849	28.3311	SPRING/EYE	AGRICULTURE: IRRIGATION	120175
26065597	-25.8796	28.2107	BOREHOLE	AGRICULTURE: IRRIGATION	35672

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26065597	-25.8796	28.2107	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	249
26065597	-25.8796	28.2107	BOREHOLE	INDUSTRY (URBAN)	944
26065597	-25.8796	28.2107	BOREHOLE	SCHEDULE 1	589
26066382	-25.8268	28.16503	BOREHOLE	RECREATION	84780
26066408	-25.9616	28.41408	BOREHOLE	AGRICULTURE: IRRIGATION	24820
26067363	-25.9642	28.3447	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	25477
26068825	-25.9502	28.2693	BOREHOLE	AGRICULTURE: IRRIGATION	150600
26070484	-25.9667	28.31667	SPRING/EYE	AGRICULTURE: AQUACULTURE	195498
26070670	-25.8859	28.211	BOREHOLE	AGRICULTURE: IRRIGATION	40149
26070670	-25.8859	28.211	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	1004
26074015	-25.9639	28.22625	BOREHOLE	INDUSTRY (URBAN)	39420
26074373	-25.9097	28.3632	BOREHOLE	AGRICULTURE: IRRIGATION	50791
26076709	-25.9783	28.364	BOREHOLE	AGRICULTURE: IRRIGATION	29400
26076727	-25.9822	28.4186	BOREHOLE	AGRICULTURE: IRRIGATION	108606
26076941	-25.9168	28.06567	BOREHOLE	SCHEDULE 1	700
26078930	-26.0542	28.24989	BOREHOLE	MINING	83428.05
26079172	-26.0043	28.31161	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	39718.6
26079877	-25.7586	28.19408	BOREHOLE	INDUSTRY (URBAN)	47304
26080044	-25.7532	28.22519	BOREHOLE	AGRICULTURE: IRRIGATION	132067.22
26080099	-25.7599	28.22192	BOREHOLE	AGRICULTURE: IRRIGATION	26280
26080099	-25.7612	28.22869	BOREHOLE	AGRICULTURE: IRRIGATION	42048
26080179	-25.8204	28.24716	BOREHOLE	INDUSTRY (URBAN)	57396
26081873	-25.9739	28.13164	BOREHOLE	INDUSTRY (URBAN)	8199.36
26082051	-26.1332	28.22215	BOREHOLE	INDUSTRY (URBAN)	6917
26082499	-25.9716	28.3705	BOREHOLE	AGRICULTURE: IRRIGATION	810480
26082541	-25.9652	28.3723	BOREHOLE	AGRICULTURE: IRRIGATION	184200
26083425	-26.0333	28.30816	BOREHOLE	AGRICULTURE: IRRIGATION	292000

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26007829	-25.9383	28.3897	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	93176
26009480	-25.8448	28.0447	BOREHOLE	AGRICULTURE: IRRIGATION	60250
26011431	-26.0562	28.2818	BOREHOLE	AGRICULTURE: IRRIGATION	25185
26013778	-25.9894	28.3314	BOREHOLE	AGRICULTURE: IRRIGATION	364327
26022660	-25.9898	28.3404	BOREHOLE	AGRICULTURE: IRRIGATION	310445
26024098	-25.9373	28.26264	BOREHOLE	MINING	29880
26024178	-25.8857	28.3839	BOREHOLE	AGRICULTURE: IRRIGATION	25023
26025603	-25.966	28.3892	BOREHOLE	AGRICULTURE: IRRIGATION	127335
26025818	-25.9046	28.0618	BOREHOLE	AGRICULTURE: IRRIGATION	5200
26026817	-25.7531	28.2299	BOREHOLE	AGRICULTURE: IRRIGATION	131300
26027022	-25.9448	28.3127	BOREHOLE	AGRICULTURE: IRRIGATION	392740
26027040	-25.7696	28.2058	BOREHOLE	AGRICULTURE: IRRIGATION	316130
26027861	-26.0309	28.1778	BOREHOLE	AGRICULTURE: IRRIGATION	2452
26028012	-26.0797	28.33167	BOREHOLE	AGRICULTURE: IRRIGATION	23949
26028227	-25.9152	28.055	BOREHOLE	AGRICULTURE: IRRIGATION	324
26029379	-25.8406	28.1355	BOREHOLE	AGRICULTURE: IRRIGATION	12745
26033248	-25.8997	28.11056	BOREHOLE	SCHEDULE 1	1760000
26033248	-25.8119	28.15917	BOREHOLE	SCHEDULE 1	711750
26033248	-25.8863	28.1213	BOREHOLE	AGRICULTURE: IRRIGATION	53371
26033248	-25.8863	28.25	BOREHOLE	AGRICULTURE: IRRIGATION	6042
26033248	-25.7914	28.19472	SPRING/EYE	SCHEDULE 1	12592500
26033248	-25.8116	28.1212	BOREHOLE	WATER SUPPLY SERVICE	252000
26033328	-25.8796	28.2107	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	128
26033328	-25.8882	28.2126	BOREHOLE	INDUSTRY (URBAN)	93406
26033328	-25.8796	28.2107	BOREHOLE	SCHEDULE 1	304
26033729	-25.882	28.261	BOREHOLE	AGRICULTURE: IRRIGATION	21965
26033952	-25.8361	28.1822	BOREHOLE	AGRICULTURE: IRRIGATION	4606

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26037654	-25.6939	28.4264	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	1168
26041685	-25.7511	28.20685	BOREHOLE	INDUSTRY (NON-URBAN)	1440
26041685	-25.7511	28.1046	BOREHOLE	AGRICULTURE: IRRIGATION	45450
26044655	-26.0944	28.31944	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	1916
26044744	-25.8796	28.2107	BOREHOLE	INDUSTRY (NON-URBAN)	275
26046635	-25.981	28.4139	BOREHOLE	AGRICULTURE: IRRIGATION	865094
26046662	-25.9769	28.4067	BOREHOLE	AGRICULTURE: IRRIGATION	341973
26047091	-25.8251	28.1137	BOREHOLE	AGRICULTURE: IRRIGATION	10100
26047572	-25.9486	28.22944	BOREHOLE	INDUSTRY (URBAN)	554800
26050095	-25.9037	28.1734	BOREHOLE	AGRICULTURE: IRRIGATION	6720
26051584	-25.9336	28.20031	SPRING/EYE	AGRICULTURE: IRRIGATION	354500
26054073	-25.7638	28.1326	BOREHOLE	INDUSTRY (NON-URBAN)	13000
26054126	-25.9723	28.3939	BOREHOLE	AGRICULTURE: IRRIGATION	48681
26054180	-25.8719	28.04267	BOREHOLE	INDUSTRY (NON-URBAN)	315
26054180	-25.8707	28.04373	BOREHOLE	INDUSTRY (NON-URBAN)	15768
26054947	-26.0958	28.2831	BOREHOLE	INDUSTRY (URBAN)	3650
26064945	-25.984	28.3565	BOREHOLE	AGRICULTURE: IRRIGATION	90182
26064972	-25.9781	28.3472	BOREHOLE	AGRICULTURE: IRRIGATION	109636
26065007	-25.9742	28.356	BOREHOLE	AGRICULTURE: IRRIGATION	111446
26066408	-25.9841	28.41688	BOREHOLE	AGRICULTURE: IRRIGATION	53728
26066408	-25.9616	28.41408	BOREHOLE	INDUSTRY (NON-URBAN)	14965
26067238	-25.9222	28.35952	BOREHOLE	AGRICULTURE: IRRIGATION	77643
26067363	-25.9642	28.3447	BOREHOLE	INDUSTRY (URBAN)	10932
26068120	-26	28	BOREHOLE	AGRICULTURE: IRRIGATION	3650
26068825	-25.9709	28.2816	BOREHOLE	AGRICULTURE: IRRIGATION	138000

REGISTRATION No.	LATITUDE	LONGITUDE	RESOURCE TYPE	WATER USE	REGISTERED ABSTRACTION (m ³ /Annum)
26068996	-25.8719	28.17667	BOREHOLE	WATER SUPPLY SERVICE	500
26069469	-26.0679	28.2823	BOREHOLE	AGRICULTURE: IRRIGATION	13347
26070554	-25.9279	28.3555	BOREHOLE	AGRICULTURE: IRRIGATION	41727
26070670	-25.8859	28.211	BOREHOLE	AGRICULTURE: IRRIGATION	14261
26070714	-25.8656	28.2016	BOREHOLE	AGRICULTURE: IRRIGATION	62013
26070796	-25.988	28.3682	BOREHOLE	AGRICULTURE: IRRIGATION	237321
26070901	-25.9352	28.3147	BOREHOLE	AGRICULTURE: IRRIGATION	734789
26074015	-25.9622	28.22381	BOREHOLE	INDUSTRY (URBAN)	12615
26074346	-25.8806	28.32946	BOREHOLE	AGRICULTURE: AQUACULTURE	2000
26074676	-25.8829	28.33197	BOREHOLE	AGRICULTURE: AQUACULTURE	2000
26074854	-25.8156	28.05483	BOREHOLE	AGRICULTURE: AQUACULTURE	3500
26076335	-25.9786	28.362	BOREHOLE	AGRICULTURE: AQUACULTURE	3650
26078529	-25.9716	28.3875	BOREHOLE	AGRICULTURE: IRRIGATION	257149
26078930	-26.0549	28.24911	BOREHOLE	INDUSTRY (NON-URBAN)	1533
26079680	-25.9618	28.14442	BOREHOLE	AGRICULTURE: IRRIGATION	10000
26080062	-25.9604	28.22272	BOREHOLE	SCHEDULE 1	3650
26080099	-25.7584	28.226	BOREHOLE	AGRICULTURE: IRRIGATION	40734
26080810	-25.9542	28.35642	BOREHOLE	AGRICULTURE: IRRIGATION	119964
26081061	-25.7638	28.11384	BOREHOLE	URBAN (EXCLUDING INDUSTRIAL &/OR DOMESTIC)	25228
26082051	-26.1339	28.22049	BOREHOLE	INDUSTRY (URBAN)	6917
26082505	-25.9629	28.3638	BOREHOLE	AGRICULTURE: IRRIGATION	773808
26083425	-26.0422	28.30673	BOREHOLE	AGRICULTURE: WATERING LIVESTOCK	2000