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Assessment of Groundwater Level Fluctuation Trends in Grootfontein Dolomite Aquifer, North West Province, South Africa

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FINAL DISSERTATION

By

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With the title:

Assessment of groundwater level fluctuation trends in Grootfontein dolomite Aquifer, North West Province, South Africa

Supervisor:

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DECLARATION

I Mr. Hulisani Thomas Rananga declare that "Assessment of Groundwater Level Fluctuation Trends in Grootfontein Dolomite Aquifer in North West Province of South Africa" is my own work. I further declare that this work has never been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

Full names:		
Signed:	*Hulisani Thomas Rananga*	***Date:*** 15***/04/2022***
Signature:		

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ABSTRACT

Groundwater level decline is a problem experienced in aquifers with more than one groundwater user such as the Grootfontein dolomite aquifer in the North West Province of South Africa. This study assessed groundwater level fluctuation trends for monitoring boreholes within municipal and irrigation groundwater abstraction areas. The study also determined the influence of rainfall and municipal groundwater abstraction as the dominant factors responsible for groundwater level fluctuation in the area. The study further recommended possible interventions for declining groundwater levels within the Grootfontein dolomite aquifer study area. Analysis of groundwater level fluctuation trend was conducted from 1980 to 2020 using Mann-Kendall and Sen's slope statistical tests. The results showed that groundwater levels in the study area had a declining trend. Spearman rank correlation was used to determine the influence of rainfall and municipal groundwater abstraction on groundwater level fluctuation within the study area. Analysis results showed that rainfall was not the main factor influencing groundwater level fluctuation as the correlation result indicated a very weak negative correlation. However, the results of correlation between municipal groundwater abstraction and groundwater level fluctuation indicated that municipal groundwater abstraction was the main factor that influenced groundwater level fluctuation within the study area as indicated by a strong negative correlation ($P < 0.001$). Correlation result for rainfall and groundwater level fluctuation was not expected as it differed from majority of literature reviewed on the topic. However, correlation result for groundwater abstraction and groundwater level fluctuation was expected. In-terms of groundwater level decline intervention, a Trigger-Level based approach was used whereby a 50th percentile zone of historical monthly groundwater level depth was adopted as the trigger level for groundwater management interventions. Monitoring of observed monthly groundwater level showed that the adopted 50th percentile of groundwater level depth was exceeded in all groundwater abstraction areas within the study area. This result therefore implied that intervention actions were needed to prevent further groundwater level decline and to allow groundwater level recovery to at least the 50th percentile groundwater level zone. The result provided a basis for implementing interventions to address observed threat on groundwater level and availability. Recommended interventions include determination of required restrictions on groundwater abstraction within the study area.

***Keywords*:** Groundwater; Rainfall; Municipal Abstraction; Fluctuation Trends; Correlation; Interventions.

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CHAPTER 1. INTRODUCTION

1.1 Background

This study investigates factors responsible for groundwater level fluctuation in order to design interventions that addresses the problem of declining groundwater levels in aquifers. A chronic groundwater level decline has been reported as a problem in many parts of the world and due to this reported problem, many studies have been conducted to investigate factors that explain such a decline. Literature review showed that groundwater level fluctuation was due to climatic parameters or human activity [Ghaleni & Ebrahimi, 2015; Malekinezhad & Banadkooki, 2018; Haas & Birk, 2019 and Zhao, *et al*., 2019].

Many studies indicated that natural induced factors play a significant role in groundwater level fluctuation. These studies argued that climate warming, reduction in rainfall intensity and frequency were the main factors responsible for groundwater level fluctuation. For example, Touhami, *et al*., (2015) reported that climate change was solely responsible for the decrease in the frequency of wet seasons in semi-arid regions and that, such a decrease resulted in a reduction of groundwater recharge. In India Basavarajappa, *et al*., (2015) reported that temperature significantly influenced groundwater table fluctuation. Tabari, *et al*., (2012) also found that decreasing trends in humidity and increasing trends in maximum and minimum temperatures correlated to groundwater level fluctuation in Iran.

There are also studies that argued that human-induced activities were mostly responsible for groundwater level fluctuation. These studies argued that a trend in groundwater level was a reverse of the trend observed in groundwater use Haas & Birk, (2019). This trend may be in the form of increasing or declining groundwater levels. In Japan, Iwasaki, *et al*., (2014) reported that paddy irrigation management influenced seasonal groundwater level fluctuation as groundwater-modelling results indicated that the aquifer was recharged by irrigation water. Increased groundwater exploitation has been found to be the main factor responsible for groundwater decline trends and land-subsidence in China Lei, *et al*., (2015).

Global and regional studies on factors that explain groundwater level fluctuation are adequate. However, such studies remain limited in Africa, and as such the context also remains limited. This situation contributes to the observed and reported lack of consistent data on groundwater level monitoring, groundwater abstraction monitoring, and climatic data. Nevertheless, Abiye, *et al*., (2018) and Ndlovu & Demlie, (2018) in South Africa conducted studies on groundwater level fluctuation trends. These studies successfully correlated groundwater fluctuation trends to rainfall variation using the Cumulative Rainfall Departure (CRD) Method with little success in correlating groundwater fluctuation to groundwater abstraction. These studies argued that where rainfall variation does not correlate to groundwater level fluctuation, even after taking into consideration groundwater response lag time, then over-pumping of groundwater could be the cause of fluctuation. The present study focused more on groundwater abstraction with the aim of designing a solution to the reported problem of declining levels of groundwater. Various studies on the effects of climate change parameters and groundwater abstraction have been carried out. Such studies have focused more on correction analysis rather than focusing on designing a solution for the reported and observed problem. The current study therefore explored the influence of groundwater abstraction and rainfall variability in groundwater level fluctuation and recommended possible intervention for declining groundwater levels in aquifer using Grootfontein dolomite aquifer as a case study.

1.2 Problem Statement

The decline in groundwater levels is a problem in aquifers. Groundwater level decline becomes a problem when factors for such a decline are not identified and assessed so that the decline as a problem can be resolved. The problem of declining levels in groundwater becomes critical when users of such waters lack information on groundwater abstraction trends. The problem of declining levels of groundwater threatens the availability of water required to sustain the livelihood through agricultural production and domestic water requirements. This means that if this situation is not addressed then benefits that come by using groundwater will not be realised. In addition, this decline suggests increasing energy consumption for pumping groundwater at a lower level in an aquifer for irrigation and domestic water supply by users. The continued decline of water levels in aquifers has the potential to create void spaces that may lead to irreversible consequences as the permanent aquifer compaction may reduce aquifer storage. In addition, the created void spaces can result in land subsidence in the aquifer as water levels continue to decline. The decline in groundwater levels has a negative ecological impact as most of the rivers and springs are groundwater-dependent thus, the declining levels of groundwater would reduce water availability for such groundwater-dependent ecosystems.

In South Africa, the problem of declining levels of groundwater has been a concern. For example, the Steenkoppies dolomite aquifer in the West Rand District Municipality, the aquifer in the Delmas area, the Polokwane Sand aquifer, and the Grootfontein dolomite aquifer. Grootfontein Eye/Spring, which used to flow at an average of 13.5 Mm^3/annum, stopped flowing in 1981 while Maloney's Eye in the Steenkoppies dolomite aquifer, which used to flow at an average rate of 13 Mm^3/annum, also ceased to flow in 2007. The declining levels of groundwater was identified as the main reason these springs ceased to flow as reported in the Department of Water and Sanitation's official report (DWA, 2013). Kanikow and Kendy (2005) report that the decline in groundwater levels is not only a South Africa problem but also a global problem as it affected many countries. For example, aquifers in countries such as the USA, India, Pakistan, and North China have experienced a groundwater decline problem [Tillman and Leake, 2010; Panda *et al*. 2007 & Shah *et al*., 2003].

1.3 Thesis statement and Research Question

The current study argues that the problem of declining levels in groundwater can be addressed when factors for such a decline are identified and assessed from a solution-based perspective. This implies that factors must be identified, categorised and assessed with methods that lead to designing interventions for such a problem. Based on this assumption, the following were the research questions: 1. what are the critical factors to declining levels of groundwater in an aquifer? 2. What interventions can be designed to address the problem of declining levels of groundwater in the aquifer system?

1.4 Study Aim

This study aims at providing an explanation of the major causes for the reported groundwater level fluctuation and decline so that a solution can be designed. This explanation will improve understanding of fluctuations of groundwater levels. Such understanding will help to design interventions as a management tool towards groundwater abstraction, planning and allocation. The present study used a semi-arid aquifer system as a case study.

1.5 Study Objectives

a. Determine temporal groundwater level fluctuation trend

b. Determine the influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline
c. Determine possible intervention for declining groundwater levels

1.6 The rationale of the Study

The present study assessed groundwater level fluctuation trends including the influence of climatic and anthropogenic activities on groundwater level fluctuation, and determined possible interventions. Groundwater level fluctuation trends and the influence of climatic and anthropogenic activities on groundwater level fluctuation have been well studied. However, there has been less focus on the interventions to groundwater level fluctuation trends and this study therefore intended to fill this gap.

1.7 Conceptualization for the study

Grootfontein dolomite aquifer is one of the most important aquifers in South Africa. This aquifer supplies domestic water for Mahikeng Local Municipality and irrigation water for local farmers. Due to its importance, the Department of Water and Sanitation has developed a comprehensive monitoring network with more than 15 boreholes and 2 rain gauge stations. However, groundwater level decline has been observed from the monitoring boreholes. This decline has reportedly caused a reduction in groundwater volume supplied to the municipality which increased the water scarcity in the area. Water scarcity and drying of boreholes as observed within the study area has motivated the researcher to undertake this study to understand factors responsible for groundwater decline and to determine possible interventions for declining groundwater levels. The topic was also chosen after an in-depth review of literature on groundwater level decline problem around the world.

1.8 Nature and Scope of the Study

This study is about groundwater level fluctuation and associated trends. The current study used the term “groundwater level” instead of water table even though they mean the same thing. According to (Lohman, 1988), groundwater level is defined by the level at which water stands in a well penetrating the top of the water body. Groundwater level can be determined by subtracting depth to groundwater (m) from land or surface elevation which is in meters above sea level (m).

This stydy was focused on addressing three ojectives which were: An assessment of temporal groundwater level fluctuation trend was conducted for the study area, determining the influence of natural and anthropogenic factors on groundwater level fluctuation, and determining possible interventions for groundwater level decline. While the concept of groundwater recharge and its components such as forms of recharge, recharge treshhold, recharge volumes etc was important in groundwater level fluctuation, this was not determined in this study. However, this study only focused on the influence of rainfall on groundwater level fluctuation.

1.9 Thesis Outline

The current study aims to cover six individual chapters. Chapter one introduces the study's topic while also providing a general background of the study topic both internationally, regionally, and locally. This background on the topic also provides theoretic framework of the study. The problem statement, research questions, objectives and rationale of the study area presented in in chapter one. This chapter concludes by providing an outline of the whole study. Chapter two presents the description of the study area indicating the study's location and attributes of the study area. Chapter three presents the literature on groundwater level fluctuation, factors that influence such fluctuation and on possible interventions to groundwater level fluctuation. Chapter four incorporates the research design and the methodology in which the study had been carried out, how the data had been obtained, where it had been obtained and how the data samples had been analysed. Chapter five presents analysis results for each objective and discussion of the results. The interpretation and implication of results is also presented in chapter 5. chapter six concludes the study providing a conclusion based on the findings of this study and suggest recommendations and a need for conducting further studies in groundwater level fluctuation trend and interventions to groundwater level decline.

CHAPTER 2. DESCRIPTION OF THE STUDY AREA

2.1 Study Location

Grootfontein dolomite aquifer as indicated on Figure 1 is located approximately 20 km southeast of Mafikeng Town and approximately 25 km northwest of Lichtenburg Town of North West Province in South Africa. The study area covers an area of 169 km² in quaternary catchment D41A of the Crocodile West and Marico Water management Area (WMA). Grootfontein study area has a flat featureless topography ranging between 1416 m above sea level to 1448 m above sea level sloping gently from the southeast to the northwestern direction with a gradient of approximately 50 m. Groundwater levels and flow is naturally controlled by the topography and as a result, many abstraction boreholes are in the northwestern area of the study.

The study area falls within Bo-Molopo Groundwater Management Area (GMA) as demarcated by the Department of Water and Sanitation due to its sensitivity to pollution and groundwater over-abstraction. This area is characterised by chert rich dolomite formation which makes it an important water bearing aquifer. The aquifer depth in the study area as determined by the Department of Water and Sanitation ranges between 30 and 60 mbgl as indicated on Figure 2. Groundwater is abstracted from different areas within the study area for municipal and irrigation use. Mahikeng Local Municipality has a groundwater abstraction license of 7.3 Mm³/a while irrigation abstraction permit is 7500 m³/ha/annum for the registered 3 792.30 hectares within the study area. The area has reported high number of dry boreholes as identified during hydrocensus conducted in 2016. This has resulted in reduced municipal water abstraction boreholes from 15 to just only 3 boreholes in 2020 which makes it inevitable to address groundwater decline problem in the study area.

Grootfontein dolomite aquifer is one of the oldest and well-developed aquifers in South Africa which are used to supply a town and irrigation activities. This aquifer has monthly groundwater level monitoring data dating as far back as 1969 for some of the boreholes. However, even with its importance in terms of water supply and with all the monitoring data, this aquifer still experienced groundwater level decline problem. This indicated a gap in application of groundwater monitoring data or system. This study area was therefore selected to understand

and address such a gap. The result obtained from this study area may be applied in other areas with similar problems.

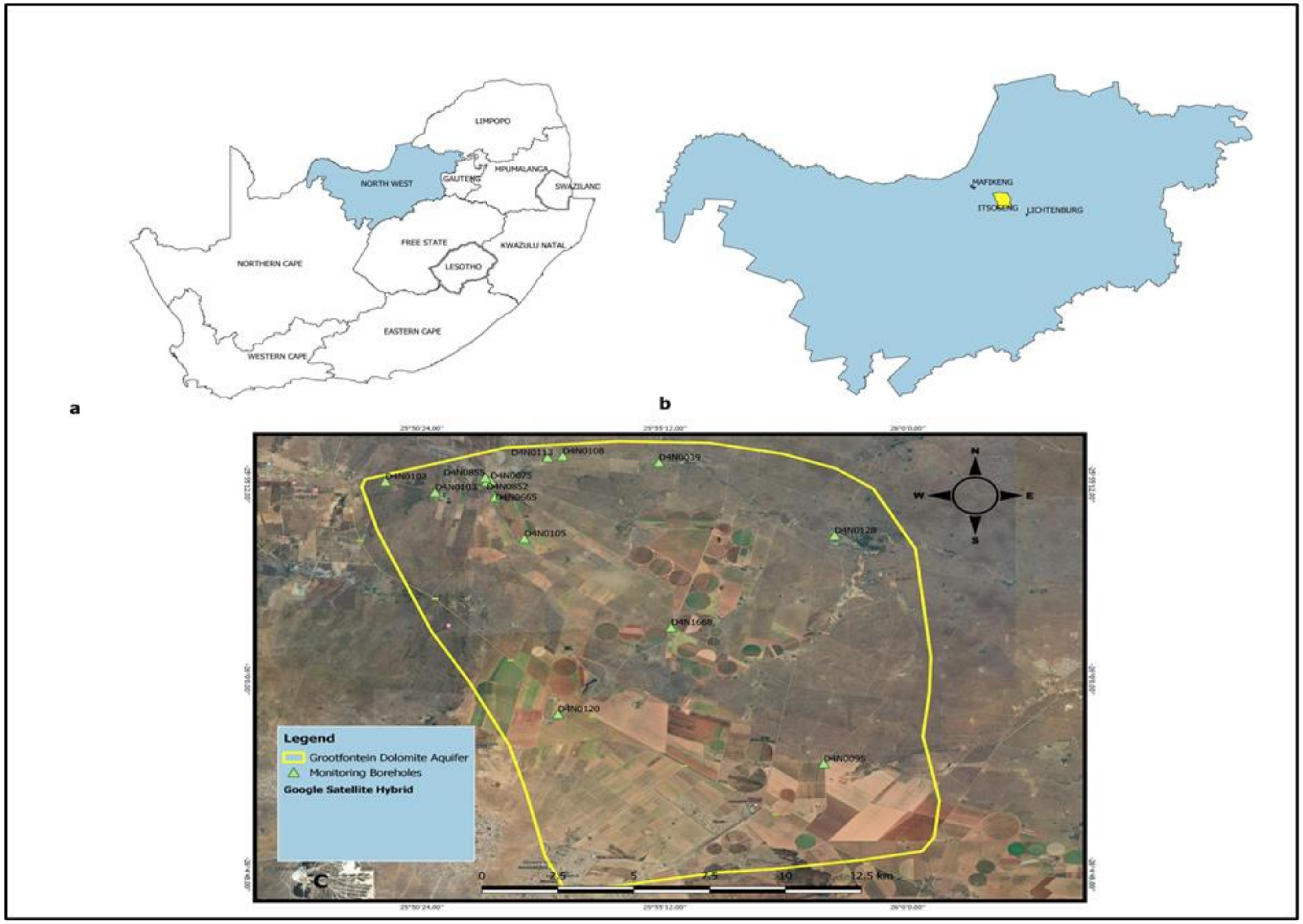

Figure 1: Study Location

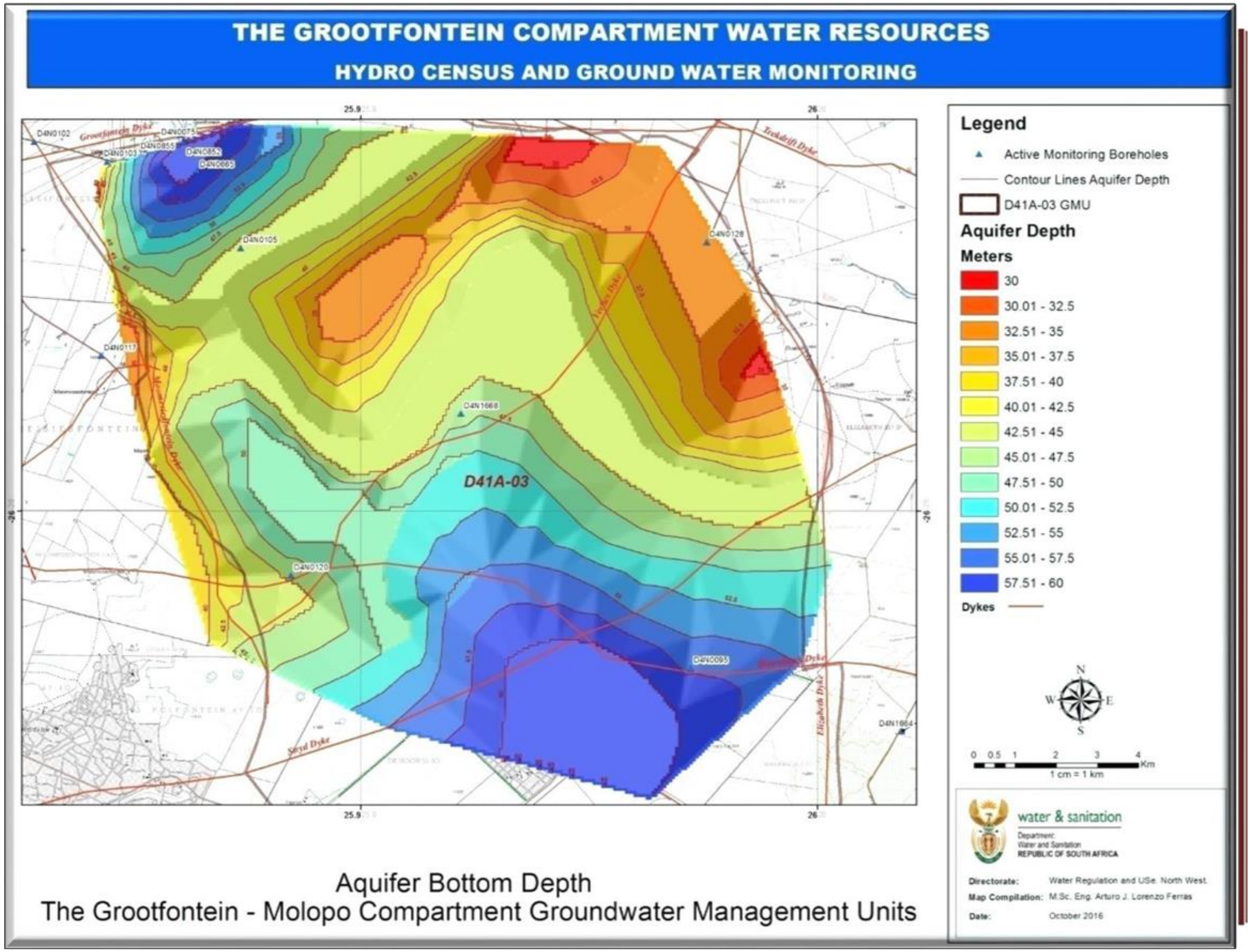

Figure 2: Grootfontein Aquifer Depth Map by Arturo J.L (2016)

CHAPTER 3. LITERATURE REVIEW

3.1 Introduction

The study's overview in terms of the introduction, problem statement, aim and objectives, and significance have been discussed in chapter one while the description of the study area was covered in chapter two. The current chapter, therefore, presented peer-reviewed literature on groundwater level trends as assessed globally, regionally, and locally with the purpose of identifying gaps in knowledge and rightfully locating the current research within the context of existing literature. A systematic and analytical review of articles based on the study objectives and framework was presented in this chapter. This section was therefore important as it assisted in identifying the knowledge gaps, common and current methods used in solving the identified groundwater decline problem.

3.2 Previous Studies to contextualise the current study on groundwater level trends

3.2.1 Global status concerning the study topic

Groundwater level fluctuation trend is an important topic in hydrology with many studies conducted globally over the years to assess, detect and quantify the magnitude of such trends. These studies investigated the factors that influence groundwater level fluctuation trends and the methods that could be used to determine such trends. For example, Akther *et al*., (2009) assessed groundwater level fluctuation in Dhaka City of Bangladesh in order to understand groundwater decline at the time. He found out that there was a falling trend in groundwater level with an average decline of 2 m per year from 1986 to 2005. Akther indicated that groundwater over-abstraction was a factor influencing the declining trend in groundwater levels. Vousoughi *et al*., (2012), who analysed fluctuation trends in groundwater, replicated Akther's findings in Iran where he found a significant groundwater decline trend at a rate of 1.8 m per year in 32 boreholes analysed from 1988 to 2009. Groundwater over-abstraction was again identified in this study as the main factor influencing the groundwater level decline trend. Abdullah *et al*., (2015), also investigated groundwater level fluctuations in Malaysia.

Recent global studies on groundwater level fluctuation trends focused on asserting if groundwater level fluctuation trends were a result of climatic factors or human activities. Examples of such studies include Haas and Birk (2019) who assessed whether trends in Australian groundwater were due to climate or human activities. Zhao *et al*., (2019) who explored the impacts of climatic and non-climatic factors on groundwater levels further assessed this in China. Krogulec *et al*., (2020) followed the same approach of identifying the causes of groundwater level change but went a step further and looked at the effects of such a groundwater level change in the Warsaw urban area of Poland.

3.2.2 Regional status concerning the study topic

Groundwater level fluctuation trend was a rarely studied topic in Africa and as such, the literature on the topic was limited. However, few notable studies on the topic were available. For example, Lutz *et al*. (2015) evaluated groundwater level fluctuation and recharge patterns in Northern Ghana focusing on the influence of precipitation on groundwater level fluctuation. Lutz concluded that seasonal groundwater level fluctuation was mainly a response to seasonal precipitation in the area. Tirogo *et al*., (2016) investigated groundwater level fluctuation trends in Burkina Faso focusing on the best methods that could be used to explain the magnitude and direction of groundwater level fluctuation trends. Gabrilla *et al*., (2018) also assessed the presence of groundwater fluctuation trends in the White Volta River Basin of Ghana of which he reported an absence of significant positive or negative groundwater level fluctuation trends on an annual scale. Gabrilla lamented the limitation of literature in groundwater level fluctuation trend topic in Africa and he attributed that limitation to the absence of dedicated monitoring systems in many African countries. The current study will therefore contribute to the limited regional literature on the topic, thereby forming a basis for future studies.

3.2.3 National status concerning the study topic

There were few studies conducted nationally on the assessment of groundwater level fluctuation. However, the Department of Water and Sanitation conducted monthly groundwater level monitoring throughout the country and produced quarterly monitoring reports that indicated the status of groundwater nationally. These reports showed the fluctuations in groundwater levels per borehole. However, such quarterly monitoring reports were not peer-reviewed and published.

The literature review on the study topic was limited to few publications by Ndlovu & Demile, (2018) and Abiye *et al*., (2018) who assessed groundwater level fluctuation trends in KZN Province and Gauteng Province respectively. These authors used the data obtained freely from the Department of Water and Sanitation and South African Weather Services (SAWS), which showed that there was a potential for more studies to be conducted on the topic as the data, was available.

The overall review of literature on the study topic has indicated that groundwater level fluctuation was well studied globally over the years but not well studied regionally and nationally. The current study intends to fill the gap in knowledge created by limited literature on a regional and national scale. The literature review also highlighted that majority of studies conducted on the topic focused on factors that influence groundwater level fluctuation and also on the methods that were used to determine groundwater level fluctuation, with less done on the interventions to groundwater level decline. The current study, therefore, intends to add knowledge by recommending interventions to groundwater level decline problem as observed in the study area.

3.3 Temporal groundwater level fluctuation trend

Understanding of temporal groundwater level fluctuation trend in aquifer is important in water resource management. Groundwater levels fluctuate monthly; seasonally, and annually and therefore water resource managers should ensure that groundwater abstraction patterns also take into consideration this temporal fluctuation to avoid groundwater depletion. Studies on temporal groundwater level fluctuations have been conducted throughout the world. These studies provided knowledge and understanding on how groundwater level fluctuation trends affect short and long-term aquifer's water availability. For example, Bui *et al*., (2012) assessed groundwater level fluctuation trend of 57 wells in unconfined aquifer and 63 wells drilled in confined aquifer using a non-parametric Mann-Kendall trend test and Sen's Slope estimator. Trends in monthly, annual, and seasonal groundwater level mean from 1995 to 2009 were analysed. The analysis result indicated that 35% of wells in the unconfined aquifer had a downward trend while 21% had an upward trend. Temporal trends in groundwater levels of confined aquifer also indicated a downward trend. Bui's study emphasized the importance of understanding how different aquifers respond to the factors influencing groundwater level fluctuation. Liu *et al*., (2017) also assessed the spatial and temporal groundwater levels of 58 observation boreholes in China. Monthly, annual, and seasonal average groundwater levels from 1993 to 2013 were determined and analyzed for temporal groundwater level fluctuation trends. Linear regression and the non-parametric Spearman's correlation method were used for analysing groundwater level trends. The result indicated an inter-annual groundwater level decline trend with the highest declining range of 2-4 meters detected between 2010 and 2013. Liu's study proved that both parametric and non-parametric methods could be used to assess groundwater level fluctuation.

Further investigations of groundwater level fluctuation trend were conducted by Bacanli, (2017), Pal *et al*., (2019) and Totaro *et al*., (2020). While these authors conducted their studies in different climatic and geological settings, they all seem to agree with Kundzewicz & Robson, (2004) and Zhang *et al*., (2006) on the point that two groups of mathematical tools used to calculate trends were parametric and non-parametric methods.

Parametric methods are slope-based tests which include T-test, F-test, simple linear regression (LR), and more advanced regressions while non-parametric methods were rank-based tests that include Mann-Kendell (MK), Sen's slope, and Spearman rank correlation (Sonali & Kumar, 2013). Parametric methods such as linear regression are very powerful in quantifying the magnitude of a trend. However, these methods needed to satisfy both the distribution and independent assumptions that data was normally distributed and independent of temporal correlations (Kundzewicz & Robson, 2004). However, hydrology data did not follow the distribution and independent assumptions, which made parametric methods less useful in detecting trends in hydrology.

Non-parametric test methods such as Mann-Kendell (MK) (Mann, 1945; Kendall, 1975) and Sen's slope estimator (Sen, 1968) were widely used for testing trends in hydro-meteorological time series as these time series were usually non-normally distributed and censured (Mahmood *et al*., 2019). These rank-based non-parametric tests were robust against missing values and generally simple to use which was an advantage against the powerful parametric test methods (Wang *et al*., 2005). Sen's slope estimator uses a linear model to estimate the sloping trend and the significance of the trend.

Mann–Kendell as the widely used rank test had challenges with the existence of autocorrelation and serial correlation in data as this affected its ability to assess the significance of a trend. This made it necessary to evaluate the time series' serial correlation before testing for trends (Yue & Hashino, 2003). However, Hamed and Rao (1998) developed a modified Mann-Kendall test for autocorrelation and Amirataee *et al*., (2016) applied this modified method successfully and this proved that Mann-Kendall statistical method was still the good in determining the trend in hydro-meteorological data.

Non-parametric test method (Mann-Kendell) was recently applied in analysing groundwater level fluctuation trend and rainfall trend in semi-arid environments like the current study area by [Valois *et al*., 2020; Nyabeze, 2019; Le Brocque *et al*., 2018 and Gibrilla *et al*., 2018]. This proved that non-parametric methods could be used with confidence even in the current study setting.

3.4 The influence of climatic parameters on groundwater level fluctuation

Climatic parameters have been noted as one of the factors that affect groundwater level fluctuation. These parameters include seasonality, temporal rainfall variability, extreme weather events, and climate change patterns.

[Dinka, *et al*., 2013; Abdullahi & Garba, 2015; Lee, *et al*., 2019 and Li *et al*. 2020] investigated the effects of seasonality on groundwater level fluctuations in different parts of the world. These studies reported that groundwater level fluctuated seasonally as a response to rainfall, temperature, and other climatic parameters. While groundwater level may fluctuate seasonally, Milne-Home, *et al*., (2017) cautioned that, the significance of each contributing factor should be analyzed and ranked to confirm the main factor influencing the fluctuation.

Rainfall variability has been widely accepted as the most significant factor that influences groundwater level fluctuation. Ndlovu & Demile, (2018) correlated a 1.5 m increase in groundwater level with an 8% increase of rainfall in the Usuthu-Mhlathuze Water Management Area (WMA) between 2004 and 2015 period. Ndlovu and Demile further indicated a correlation between groundwater level decrease and decrease in rainfall for the period 2004 to 2010 in the northern uThukela WMA. These authors noted that the periods with decreased groundwater level was associated with below-normal rainfall and sporadic droughts while the periods with increased groundwater level was associated with above-normal rainfall and sporadic floods.

Droughts and floods were extreme climatic events that influence groundwater level fluctuations. Inter-governmental Panel on Climate Change (IPCC) (Mackay, 2008) reported that climate change was occurring on a global scale and that this change was resulting in increased flooding and drought events. Global climate change was characterised by a decrease in duration and intensity of precipitation and the increase in the frequency of floods and drought as extreme events. The increase in the frequency of extreme climatic events negatively influenced groundwater recharge as much of the rainfall resulted in the runoff with less infiltration (Lee *et al*., 2019). While the influence of climate change and extreme climatic events on groundwater level fluctuation was undoubted, Goderniaux *et al*., (2015) indicated that the sensitivity of groundwater level fluctuation in response to climate change was associated with aquifer characteristics such as; aquifer size, aquifer type, groundwater level depth, geological features, etc. The current study therefore considered the mentioned aquifer characteristics when assessing the influence of climatic parameters on aquifer groundwater level fluctuation.

The influence of climatic parameters on groundwater level fluctuation could be assessed using different methods. For example, Zhao *et al*. (2019) analyzed the impact of climatic and non-climatic factors on groundwater level fluctuation by first defining climatic phases as dry, normal, and wet phases using rainfall anomalies. Zhao then used the Mann-Kendall test and Sen's Slope methods to assess the influence of temperature and rainfall on groundwater levels. The result indicated that dry, normal, and wet phases occurred alternatively and that, while groundwater level decline trend was significant during the dry phase, it did not recover completely during the wet phase. Lee *et al*., (2019) successfully used a similar approach to that of Zhao *et al*. (2019) in assessing the influence of climatic factors on groundwater level fluctuation. In his study, Lee compared meteorological and groundwater drought conditions to infer the relationship between precipitation deficit and groundwater level decline. Meteorological drought was determined using the Standardized Precipitation Index (SPI) at a 12-month time scale while groundwater drought was determined by the standardized groundwater anomaly. Bacanli (2017) also used the SPI, Mann-Kendell, Spearman's rho tests and linear regression in assessing the influence of rainfall on groundwater level fluctuation by comparing the trends in precipitation with the trends in groundwater level fluctuation. Bacanli concluded that precipitation decline trend was parallel to groundwater decline trend.

Linear regression was another method used to assess the influence of climatic parameters on groundwater level fluctuation. Haque, (2021) used linear regression to compare the relationship between annual precipitation patterns and groundwater patterns in Dhaka City of Bangladesh. Hague concluded that groundwater fluctuation patterns were related to precipitation fluctuation patterns. Regression procedures were also successfully used in assessing the influence of climatic parameters on groundwater levels by Thomas and Famiglietti, (2019).

Correlation method has also been used successfully in determining the influence of climatic parameters on groundwater level fluctuation. This method includes cross-correlation, auto-correlation and correlation coefficient. Kulakarni *et al*., (2020) assessed the influence of rainfall, evapotranspiration, humidity and recharge on groundwater level fluctuation in Manvi, India. In conducting this assessment, auto-correlation function, partial correlation function and cross-correlation function were to determine lag-time in climatic parameters as input to the model. The results indicated that rainfall and evapotranspiration had a good correlation with groundwater level fluctuation with a 1-month and 4-month lag-time for rainfall and evapotranspiration respectively. Correlation method was also used successfully in determining the influence of rainfall, relative humidity and temperature on groundwater level fluctuation by [Singh and Borrok, (2019); Milewski *et al*., (2019) and Tabari *et al*., (2012)]

The review of methods used to assess the influence of climatic parameters on groundwater level fluctuation revealed that:

- Mann-Kendall and Sen's Slope methods were good in determining groundwater fluctuation trend and slope of the trend; however, these methods were not best in determining the influence or relationship between 2 variables such as groundwater level fluctuation and precipitation as they did not take into account the response lag-time between the 2 variables and therefore should be used with caution. However, Zhao *et al*., (2019) demonstrated how these methods could be best used to achieve the intended result.

- Linear regression and other regressions may be used to assess the influence of precipitation on groundwater fluctuation trends on an annual basis. However, Hague, (2021), Thomas and Famiglietti, (2019) did not indicate how the effects of groundwater response lag-time to precipitation was accounted for in this method. Linear regression also does not provide information on how strongly the variables are related to one another.

- Correlation method was found to be more suitable in determining the influence of climatic parameters on groundwater level fluctuation as compared to the other methods discussed. Correlation was defined as the measure of monotonic association between two variables (Schober, Boer and Schwarte, 2018). This method did not only indicate the influence of one variable by another but indicated the direction and the strength of such an influence.

3.5 The influence of anthropogenic activities on groundwater level fluctuation

Anthropogenic activities influence groundwater level fluctuation. These activities include land-use change and groundwater abstraction. Anthropogenic activities were normally associated with the reduction in groundwater levels. Groundwater over-abstraction has been noted as the main anthropogenic activity influencing the reduction in groundwater storage. For example; Gu *et al*., (2017) assessed groundwater level fluctuations and its response to natural and anthropogenic factors in Beijing, China. A cross-correlation analysis was applied to investigate the influence of natural processes and human activities in groundwater level fluctuation. Gu reported a continuous groundwater level decline from the trend analysis performed while the correlation result indicated a declining trend of groundwater level which was attributed to excessive groundwater exploitation in the area. The influence of excessive abstraction on groundwater level fluctuation was corroborated by (Oh *et al*., 2017) who reported that, groundwater levels showed a continuous decline trend when groundwater exploitation was greater than the recharge.

Anthropogenic activities were also associated with the positive fluctuation of groundwater levels through increased aquifer recharge. The positive fluctuation in groundwater levels was noted in Japan (Iwasaki *et al*., 2014). Iwasaki reported that groundwater levels increased in paddy fields wherein rice and crop plantation were rotated. The reported increase in groundwater levels was noted to increase in a period coinciding with the ploughing, preparation and irrigation of rice. Abiye *et al*., (2018) also noted a continuous increase in groundwater levels both in shallow and deep aquifers within the radius of previously de-watered Johannesburg defunct gold mines and attributed the increased in groundwater level to the cessation of the mining activities in the area. Significant groundwater level increases were further detected in Southern Virginia due to the cessation of groundwater withdrawal from one of the biggest groundwater user in the region (Dong *et al*., 2019). While groundwater time's series were analysed for groundwater level fluctuation trends in all these studies, no correlation analysis was performed to determine the significance of the factors influencing groundwater level fluctuations. This raised questions of what if there were other factors responsible for the reported groundwater level fluctuations in those studies. It was therefore important that the magnitude of possible factors influencing groundwater level fluctuation be determined to correctly associate the most significant factor with groundwater level fluctuation. Halder *et al*., (2020) correctly associated declining groundwater levels in wells with the decrease in dense forest cover from 10.88% in 1989 to 4.93% in 2018 using correlation method. The authors indicated that such a decrease in the forest cover increased bare land and reduced the water holding capacity of soil and run-off increased resulting in poor aquifer recharge in the study area.

While correlation method was widely used in determining the relationship between anthropogenic factors and natural factors with groundwater fluctuation, it was also noted that this method did not assure that the relationship between anthropogenic factors and groundwater level fluctuation was causative (Schober *et al*., 2018). Singh & Borrok, (2019) conducted the first Granger Causality analysis to identify the cause of groundwater fluctuation patterns in Louisiana, USA. They reported that, causal linkages were absent between groundwater level fluctuation and many drivers where significant correlation was noted. These authors therefore recommended the use of robust causal relationships instead of the "illusive correlations" to determine the cause of groundwater level fluctuation. It was therefore important for a researcher to choose the right terminology due to the differences between the determination of causes for groundwater level fluctuation and the determination of factors influencing groundwater level fluctuation.

3.6 Intervention for declining groundwater levels

Ground water level decline has been widely reported as a problem effecting aquifers both regionally and globally. While the magnitude of groundwater level decline, the causes and impacts for such a decline were well reported, interventions for groundwater level decline were not so well documented. Nevertheless, consensus agreement established from the limited literature reviewed was that, both scientific and social based management approaches were important interventions for groundwater level decline.

The scientific based groundwater management approach for an aquifer was also referred as a "controlled groundwater abstraction" management approach. This management approach was informed by a numerical groundwater model run for an aquifer under different abstraction scenarios to predict groundwater level fluctuations and flows (Anderson *et al*., 2014). However, it was not always conducive to re-run these models each time for new abstraction scenarios. Therefore, simple groundwater management tools were developed based on the numerical model already run or expert opinion (Noorduijn *et al*., 2019). The commonly used tools were flux based and trigger-level based groundwater management tools.

Flux based groundwater management approach also known as volumetric allocation approach, involves determination and setting of total permissible annual groundwater abstraction volume for an aquifer or a water management area. This permissible abstraction volume was referred to as a "safe yield" (Bredehoeft, 1997). The total permissible annual abstraction volume was normally set at a volume equal to recharge volume for an aquifer or water management area. Bredehoeft's approach of setting a safe yield volume equaling the recharge volume has been criticized with some authors referring it as "an over simplification" of aquifer's groundwater dynamics (Alley & Leake, 2004 ; Gleeson *et al*. 2010). Anderson *et al*., (2014) urged that the safe yield should be set as a fraction of recharge, or it should be set based on sustainable historical abstraction rate in order to protect an aquifer. However, Currell (2016) urges that the use of sustainable historical abstraction rate may only work if the aquifer has reached a steady state of which it may take hundreds of years before this steady state was reached and therefore advocated for use of recharge instead of a sustainable historical abstraction rate. The use of volumetric allocation approach has been found to limit the long-term impacts of abstraction while also providing a stable and secure supply for groundwater users. However, its disadvantage was that it did not consider spatial distribution of recharge and discharge in an aquifer thus rendering it poor in protecting groundwater depended ecosystems (GDE) (Noorduijn *et al.*, 2019).

Groundwater level trigger was also used as a management approach to protect aquifer's groundwater depletion. This method involved setting of permissible drawdown level/range for an aquifer relative to baseline at a particular monitoring borehole and when that range was exceeded, intervention actions were triggered (Currell, 2016b and Werner *et al*., 2011). Cutting back on groundwater pumping was the main intervention action employed when groundwater trigger level/range was exceeded. Groundwater trigger level-based approach was often used for aquifers where groundwater recharge was negligible and in aquifers were the available resource was insufficient to supply the demand. Grootfontein dolomite aquifer is an example of aquifers where groundwater resource was insufficient to supply the demand.

There were many advantages of using trigger level-based management approach such as; that the method was more inclusive as it allowed the inclusion of water quality, groundwater level trends and ecosystem health as indicators or triggers in an aquifer. This method did not require prior estimation of groundwater recharge, it considered spatio-temporal variability of groundwater abstraction and recharge and was therefore was found to be easy to use (Werner *et al.*, 2011).

Trigger level-based management approach also had limitations. This method only worked where trigger levels and management actions were determined (Noorduijn *et al.*, 2019). However, determination of trigger levels and management response actions was not only based on the science but also on stakeholder's acceptance, which may be not easy to achieve especially for aquifers with different users like the Grootfontein aquifer in North West Province. However, Azizi *et al*., (2017) suggested the use of bottom-up institutional agreements where management approaches required stakeholder's approval to succeed. The other limitation was a challenge in consistently conducting monitoring and assessment of groundwater level draw-down as a result of new activities and natural factors such as climate change that made it difficult to trigger management actions (Matthew J. Currell, 2016).

The advantages and disadvantages for using both the flux-based management and trigger level-based management approaches were indicated. While it might not always be easy to choose between flux based and trigger level-based management approaches, a combination of these methods was recommended for use in an aquifer for better intervention response to groundwater level decline (Noorduijn *et al*., 2019; Currell, 2016b and Werner *et al*., 2011).

3.7 Theoretical and Conceptual Framework

This study was based on two theoretical frameworks which were the Law of Water Balance by (Dębski, 1963) and the Fluctuation Theorem by Evans & Searles, (2002). The Law of water balance states that, the inflows to any water system or area was equals to its outflows plus change in storage during a time interval. This law therefore inferred that equilibrium was reached when the inflow was equals to the outflows plus change in storage. The variables used in the water balance were precipitation and evaporation. However, groundwater abstraction was used instead of evaporation in this study.

Fluctuation theorem was another fundamental theory underpinning this study. This theorem states that, there was a relative probability that the entropy of a system which was currently away from thermodynamic equilibrium will increase or decrease over a given amount of time. This theorem originated from statistical mechanics whereby it explained thermal fluctuation of variables such as pressure, temperature, or entropy. However, as the current study deals with the assessment of groundwater level fluctuation, groundwater level was the main variable used. This theory therefore assumed that groundwater level will fluctuate if equilibrium in the aquifer system was not reached.

The two theories will guide approaches to be taken in this study towards addressing the identified groundwater level decline problem. The conceptual framework for this study was that groundwater level fluctuates due to non-equilibrium state of the aquifer whereby rainfall was either higher than groundwater abstraction or whereby groundwater abstraction was higher than rainfall.

3.8 Research and interpretation framework

The theorical frameworks used in this study assisted in understanding and interpreting analysis results for the first and second objectives. The first objective was to determine groundwater level fluctuation while the second was to determine the influence of rainfall and groundwater abstraction on aquifer groundwater level fluctuation. According to these theories, changes in aquifer groundwater storage may remain constant if rainfall was equals to groundwater abstraction. However, downward of upward fluctuations may be experienced at the aquifer if precipitation was higher than groundwater abstraction of vice versa.

3.9 Summary chapter/overview on gap analysis

Chapter two presented peer-reviewed literature on groundwater level trends as assessed globally, regionally, and locally with the purpose of identifying gaps in knowledge and rightfully locating the current research within the context of existing literature. A systematic and analytical review of articles based on the study objectives and framework was presented in this chapter. The literature review indicated that groundwater level fluctuation analysis was not a widely studied concept in Africa mainly due to the lack of consistent monitoring data for both groundwater levels and rainfall. The literature review also highlighted that majority of studies conducted on the study topic focused on factors that influence groundwater level fluctuation and, on the methods, used to determine groundwater level fluctuation, with less literature on interventions and solutions to groundwater level fluctuation trend. The current study, therefore, intends to add knowledge by determining possible interventions to groundwater level decline problem as observed in the study area.

CHAPTER 4. RESEARCH DESIGN AND METHODOLOGY

4.1 Introduction

Chapter one provided the study's main objectives, scientific research problem and research question while chapter two described the study area. Literature review on groundwater level fluctuations, groundwater level decline and interventions for groundwater level decline was conducted in chapter three. Different methods for determining groundwater level fluctuation and the influence of natural and anthropogenic factors in groundwater level fluctuation were reviewed together with different interventions to declining groundwater levels. The current chapter describes data needed to address this study's objectives, methods used in collecting such data and how the data was analysed. This chapter argued that detailed description on research design, methods for data collection and analysis and research integrity were fundamental in providing a basis for reliability and validity of the research results, and sound interpretation and implication of the results.

The general approach to this study was a case study approach whereby Grootfontein dolomite aquifer in North West Province of South Africa was used. This aquifer was important as it was the biggest source of water supply to Mahikeng Local Municipality in North West Province. A comprehensive approach in determining the appropriate research design, appropriate data required, its collection and analysis methods was adopted for this research study as presented in this chapter.

4.2 Research design

4.2.1 Research Design

Research design provides a plan on how research problem and study objectives will be addressed. This plan gives details on the type of data needed, how and where it would be collected and analysed and how it would be interpreted. The current study was dealing with a problem of aquifer groundwater level decline. It was argued in this study that improved understanding on factors for declining groundwater levels need to be holistically documented from impacts that come from such decline as such understanding may form a basis for interventions.

The current study used statistical methods in describing groundwater level decline and in assessing the influence of both natural and anthropogenic factors on groundwater level decline in the study area. Hence, the study employed descriptive research design. Descriptive research design describes the characteristics of a phenomenon or situation studied and determines the frequency at which the phenomenon or situation occurs and its associated variables (Kothari, 2004).

4.2.2 Methods for sampling design

Sampling design explains the procedure used to obtain a sample from the population or universe. Population in this context referred to all 10-groundwater level monitoring boreholes and three (3) rainfall monitoring stations in Grootfontein aquifer study area while a sample referred to a group of boreholes and rainfall station selected for analysis in this study.

Non-probability sampling design was chosen for this research. In non-probability sampling, participants are chosen deliberately by the researcher because they are available, convenient or represent a characteristic the researcher wants to study. This method of sampling was also known as purposive sampling, deliberate sampling, and judgmental sampling (Kothari, 2004). In the current study, the sample members had sufficient length of data and were in areas of interest to the researcher. Within this context, sample participants were water level monitoring boreholes with annual groundwater level data of more than 30 years, located within the Grootfontein aquifer wellfield and covering two domestic groundwater abstraction areas and an irrigation abstraction area as the main groundwater abstraction areas. Three (3) water level monitoring boreholes and one (1) rainfall monitoring station were therefore selected as sample members based on the mentioned criteria. The information on the sample chosen is indicated on Table 1.

Table 1: Research Sample

Sample ID	Sample Coordinates		Data Length
Mafikeng WO Rainfall Station	-25.81700	25.5500	1980-2020
Borehole D4N0075	-25.9185	25.86256	1980-2020
Borehole D4N0103	-25.9233	25.8442	1980-2020
Borehole D4N0105	-25.9423	25.8737	1980-2020

4.2.3 Data type and their sources

Secondary data was used in addressing the objectives and research questions. Secondary data is data that has already been collected and analysed by someone else and the example of such data include public records, statistics, historical documents, data from journals etc.

Secondary data used in this study was monthly rainfall from the South African Weather Services (SAWS), monthly groundwater level data from Department of Water and Sanitation and monthly groundwater abstraction data from Sedibeng Water Board.

4.3 Methodological approach

The current study aimed to understand factors for groundwater decline problem and to determine possible interventions for such a problem in Grootfontein aquifer. The study approach was to assess temporal groundwater level fluctuation and to determine the influence of natural and anthropogenic factors on groundwater level fluctuation. Quantitative data expressed in numbers was collected from secondary sources and analysed using statistical methods explained in section 3.4. The result for such analysis were expressed in graphs and tables to present a generalized understanding of the research problem. This study therefore followed a quantitative methodological approach, which was commonly used in similar research studies.

Research may also use a qualitative methodological approach that collects its data using questionnaires and expresses such data in words. However, this approach was not suitable for this study as data was collected from secondary sources while represented in numbers.

4.4 Research Methods

4.4.1 Data collection and analysis methods for groundwater level fluctuation trend

The study's first objective was to determine temporal groundwater level fluctuation trends in Grootfontein aquifer. Secondary data in the form of monthly groundwater level was obtained from Department of Water and Sanitation. The start of groundwater level data varied from 1970 to 1979 for the three sample stations. It was therefore decided that the analysis for groundwater level fluctuation would begin in January 1980 to January 2020 as all the stations had data from 1980.

Monthly groundwater level data from the sample stations was prepared for analysis by identifying missing data and possible outliers. Microsoft Excel was used to fill-in the missing data through linear interpolation. In a case where a sample borehole had a logger that recorded multiple groundwater levels per month, an average monthly groundwater level was calculated from such records. Average annual groundwater levels were calculated for each sample station from the monthly data.

A time series analysis was conducted by plotting annual groundwater level fluctuation from January 1980 to January 2020 to determine the measures of central tendency, peaks, cycles etc. in groundwater level data. Non-parametric statistical methods in the form of Mann-Kendall and Sen's slope were then used to analyse groundwater fluctuation trend for each sample data. Non-parametric statistical methods were preferred in determining fluctuation trend for groundwater level data in the study area as these methods did not require data to be normally distributed and the methods were also good for analysing monotonic trends in hydro-climatic data. Mann-Kendall and Sean's Slope methods were executed in MAKESENS excel template developed by (Salmi, *et al.*, 2002). Mann-Kendall test statistics (S) was calculated as ((Mann, 1945); (Kendall, 1955)):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_{j-x_i}\right) \qquad (1)$$

Wherein sgn was the signum function. Application of the trend was applied on an annual average groundwater level time series data x_i ranked from $i = 1,2 \ldots \ldots, n-1$ and x_j, ranked from $j = i+1,2, \ldots\ldots n$. Each data point x_i was used as a reference point and was compared with the test of data points x_j such that

$$sgn\left(x_j - x_1\right) = \begin{cases} 1\ if\ \left(x_j - x_i\right)\ > 0 \\ 0\ if\ \left(x_j - x_i\right)\ = 0 \\ -1\ if\left(x_j - x_i\right)\ < 0 \end{cases} \qquad (2)$$

If $n < 10$, the the value of S was compared directly to the theoretical value of S derived by (Mann, 1945 and Kendall, 1955). At certain probability level, H_0 was rejected in favour of H_1 if the absolute value of S equals or exceeded a specified value $S_{a/2}$, where $S_{a/2}$ was the smallest S which has probability less than $\alpha/2$ to appear in a case of no trend. A positive value of S indicated an increasing trend whereas a negative value of S indicated a decreasing trend. The p value of the Mann-Kendall test indicated the presence or absence of significant trends. Therefore, if the calculated value of $p > p_a$, the null hypothesis (H_0) was rejected at α level of significance in two-tailed test. The $n = 10$, Mann-Kendall statistics S was approxiamtely normally distributed with a variance, $Var(s)$.

The variance statistics was given by equation 3 as:

$$Var(S) = \frac{n(n-1)(2n+5) + \sum t_{i(t_i-1)}(2t_i+5)}{18} \qquad (3)$$

Where t_i was the number of ties present with i as extent. The significant level trend as an important parameter was evaluated using the standardised test statistics, Z_c:

$$Z_c = \begin{cases} \dfrac{s-1}{\sqrt{Var(S)}}\ if\ S > 0 \\ 0\ if\ S = 0 \\ \dfrac{s+1}{\sqrt{Var(S)}}\ if\ S < 0 \end{cases} \qquad (4)$$

A positive Z_c indicated an upward (increasing) trend while a negative value indicated a downward (decreasing) trend. Standardised Mann-Kendall statistic Z_c followed a standard normal distribution. A two-tailed test at 0.1 significance level was used to determine an increase or decrease in trend.

It was also necessary to determine the slope of the detected trend as it provided the magnitude of the trend. Sen's slope estimator(Q) was used for this purpose, as it was an unbiased estimator of trends with high precision than other methods. The magnitude of the trend was estimated as:

$$(Q_i) = \frac{x_j - x_k}{j-k} \; for \; i = 1.2, \dots, N, \qquad (5)$$

Where x_j and x_k were the data values at times j and $k(j > k)$, respectively. The median of N values of Q_i was represented as Sen's slope estimator. $Q_{med=Q_{(n+2)/2}}$ if N was even. A positve value of Q indicated an increasing trend while a negative value indicated a decreasing trend in the groundwater level time series data.

4.4.2 *Data collection and analysis methods for the influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline*

The second objective was to determine the influence of climatic parameters and anthropogenic factors on groundwater level fluctuation. Climatic parameter for this study was the rainfall while groundwater abstraction was the anthropogenic factor. Secondary data in the form of annual groundwater level, rainfall and groundwater abstraction was used for this objective. This data was collected for analysis from Department of Water and Sanitation, South African Weather Services and Sedibeng Water Board respectively.

Data preparation was conducted for groundwater level, rainfall and groundwater abstraction data whereby gaps and possible outliers in data were identified. Since groundwater level data was already prepared on objective one, rainfall and groundwater abstraction data were analysed for missing data and possible outliers. However, this data was suitable for use as it had no gaps and outliers.

The influence of rainfall and groundwater abstraction on groundwater level fluctuation was determined by running a correlation analysis between the two variables i.e. (annual rainfall fluctuation data and annual groundwater level fluctuation data) from 1980 to 2020. A correlation analysis was also conducted for the other two variables i.e. (annual groundwater abstraction data and annual groundwater level fluctuation data) for the same period. The conditions and hypothesis required for using Pearson and Spearman correlation methods were evaluated from the literature. It was found that Pearson correlation was suitable for normally distributed data while Spearman rank correlation was perfect for data which was not normally distributed (Fowler, *et al*., 2009). Hydro-climatic data used for this analysis was not normally distributed and therefore Spearman correlation test was used for analysis. The relationship/association between the two variables could not be predicted to be either in positive or negative direction and therefore a two-tailed significance test represented by a p-value was conducted.

A bivariate Spearman rank correlation (Spearman, 1904) analysis was run on IBM Statistical Package for Social Sciences (SPSS) software platform to determine the strength and direction of association between the two variables. Spearman rank correlation determines monotonic association between two variables and it was important to emphasize that this association did not assure that the relationship was causal (Schober, Boer and Schwarte, 2018). To prove the correlation between variables, a null hypothesis H_0 and alternative hypothesis H_1 were set. The null hypothesis meant that there was no correlation while alternative hypothesis indicated that there was correlation between the two variables.

Spearman rank correlation used formula six (6) to prove the null and alternative hypothesis for correlation between two variables:

$$r_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \qquad (6)$$

Where r_s= Spearman Rank correlation coefficient, D_i= the difference between the rank of n was the sample size. The spearman correlation coefficient may be a value between +1 and -1 whereby +1 indicates a perfect positive association and -1 indicates a perfect negative association while 0 indicated no association between variables. The closer r_s was to zero, the weaker was the association between variables (Fowler, *et al*., 2009) as indicated on Table 2.

Table 2: Spearman Correlation Strength

The strength of a correlation	
Value of coefficient R_s (positive or negative)	**Meaning**
0.00 to 0.19	A very weak correlation
0.20 to 0.39	A weak correlation
0.40 to 0.69	A moderate correlation
0.70 to 0.89	A strong correlation
0.90 to 1.00	A very strong correlation

The probability that the obtained correlation was due to chance was also measured by the p-value. This P-value ranged between 0 (0%) and 1 (100%). A p-value close to 1 suggested no correlation other than due to chance which therefore meant that the null hypothesis was correct while a p-value of close to 0, suggested that the observed correlation was unlikely to be due to chance and that there was a very high probability that the null hypothesis was wrong. In case of p-value close to 0, we therefore accept the alternative (H_1) hypothesis which states that there was a correlation between the two variables. Table 3 indicated the correlation significance level for rejecting and accepting the null hypothesis.

Table 3: Correlation Significant Level Measure

P-value and evidence for rejecting the H_0 null hypothesis		
P-value	**P-value %**	**Evidence for rejecting H_0**
More than 0.1	>10%	Very weak to none
Between 0.1 - 0.05	10%-5%	Weak
Between 0.05 - 0.01	5%-1%	Strong
Less than 0.01	<1%	Very strong

4.4.3 *Data collection and analysis methods on possible interventions for declining groundwater levels*

The third objective was to determine possible interventions for groundwater level decline. Average monthly groundwater level data obtained from Department of Water and Sanitation and prepared in objective one was used.

Volumetric and Trigger-level based (TLB) methods as indicated in literature review section of this study were the main scientific methods suitable for groundwater level decline intervention. However, volumetric method as indicated in literature, required that a detailed assessment of aquifer's safe yield be conducted for groundwater level decline intervention. There are many approaches and on-going debate on the determination of aquifer's safe yield and this research could not venture into that topic due to limitation in time. It was therefore decided that a less complicated but equally effective trigger-level based method would be used for interventions to groundwater level decline.

Triger-level based groundwater management method involved determination of a drawdown level at each individual sample site of which when exceeded, groundwater level decline interventions would be triggered. Average monthly groundwater level data from 1980 to 2020 was analysed and ranked into different percentiles from the 5th to the 95th percentile to determine the trigger level. The 5th percentile indicated the shallow groundwater level while the 95th percentile indicated the deepest groundwater level zone computed at each sample location. A 50th percentile indicated an average groundwater level zone computed at the sample location. This average/median groundwater level zone was therefore chosen as the trigger-level at which when exceeded, interventions were triggered. The 50th percentile groundwater level zone was conservative especially when considering that the maximum borehole depth was between 40 and 50 mbgl and therefore operating at that level could protect boreholes from drying.

Observed monthly groundwater level from October 2018 to January 2020 was plotted against the percentiles in each groundwater sample location to determine when the trigger-level zone has been exceeded.

4.5 Quality assurance/Quality control: Correct collected data

4.5.1 Evidence on adequacy of the collected data

Adequacy of the collected data refers to the sufficiency of data collected in addressing research questions and objectives of the study. The aim of the study was to assess groundwater level fluctuation trends and factors that influence such trends in order to determine interventions for groundwater decline problem in the study area.

Monthly groundwater level data, rainfall, and abstraction data from January 1980 to January 2020 was collected for analysis in addressing research objectives. This data was considered long-term and adequate for hydrological analysis due to its record length of 40 years. A minimum data frequency standard of 30-year record was commonly accepted by hydrologist in difference parts of the world based on probability theory and regional hydraulic experiences (Onyutha, 2016). Therefore, data collected for this study was adequate for analysis and its results may be accepted.

4.5.2 *Evidence on reliability of the collected data*

Reliability refers to the likelihood of obtaining the same results when the same variables are measured more than once by a researcher or any other individual (Brink, 1993). Groundwater level was calculated daily using data loggers and monthly using a deep meter. There were no changes in the measuring devices used. Batteries in boreholes data logger were replaced before the ran out of power thereby maintaining the consistency of data. However, reliability on groundwater abstraction data was low as the flow meters recording domestic groundwater abstractions were sometimes not working due to lack of maintenance as observed during the site visits. The weather station used for rainfall data collection had full data for all the months from 1980 to 2020 and therefore this data was reliable.

4.5.3 *Evidence on validity of the collected data*

Validity in data collection refers to the extent to which the data collected may correctly address research questions and objectives. Collar height was subtracted for each groundwater level calculations to determine groundwater level. The study area had 10 monitoring boreholes with different length of groundwater level data record and these boreholes were used to calibrate the sample boreholes' data to improve accuracy of data.

Rainfall data was recorded daily in three weather stations belonging to the South African Weather Services while a separate rain gauge of the department of Water and Sanitation was also available to record rainfall within the study area near borehole D4N0075. While data from all rainfall stations had different starting date and record length, similar rainfall records were identified for corresponding years in all rainfall weather stations therefore increasing validity on data collected for this study.

Groundwater abstraction data used for this study was not a true representation of abstractions taking place in the study area as this data was for only the three boreholes recording municipal groundwater abstractions while irrigation abstraction in the study area was not monitored.

Normality test was conducted to validate the use of non-parametric methods in data analysis for this study. One of the common properties for all normally distributed data was that the mean, median and mode were all equal (Patel & Read, 1996). However, the mean, median and mode were different for all samples used in this study as indicated on Table 4. This therefore validated the use of non-parametric statistical methods for data analysis.

Table 4: Data Statistics for research samples

Statistics

		D4N0075	D4N0103	D4N0105	Rainfall	Abstraction
N	Valid	41	41	41	41	41
	Missing	0	0	0	0	0
Mean		21.5539	20.8217	30.4968	512.761	5.1454
Median		21.6100	20.6100	32.3700	499.400	4.4100
Mode		3.45[a]	5.98[a]	13.29[a]	292.7[a]	4.41
Skewness		-.338	-.412	-1.038	.532	1.322
Std. Error of Skewness		.369	.369	.369	.369	.369

4.6 Research Integrity

4.6.1 Theoretical requirements on research integrity

Integrity is an important aspect in any research as the value and benefits of a research are vitally dependent of it (Resnik & Shamoo, 2011). While aspects of research integrity may differ depending on the nature of research, the country's standards on research and other things, four main principles of research integrity were identified during the 2010 Second World Conference on Research Integrity in Singapore. The four main principles for research integrity were honesty, accountability, professionalism, and stewardship.

4.6.2 Application of the principles of the research integrity

The researcher has applied the four principles of research integrity applicable to this study as indicated below:

(a) Honesty and accuracy

The current research study relied on secondary data due to its nature. The researcher was honest when requesting for data at the Department of Water and Sanitation and the South African weather Services. The researcher also signed disclaimer forms that the data received would not be shared or used for any other purposes beside this research and that he will acknowledge these institutions for assisting him with data.

The researcher applied care during data preparation ensuring that the data was accurate for its intended use. He also followed sound scientific methods in data analysis as guided by available literature on this research topic.

(b) Professionalism

The researcher acted professionally during this research by acknowledging the work done by other authors through referencing. The researcher also acknowledged other people and institutions that contributed to the success of his work in other ways such as funding, peer reviews, tutorials, advice etc.

4.6.3 *Operationalising responsibilities on ethical conduct of research*

Research ethics provide guideline on how to responsibly conduct research. While most ethical responsibilities apply in qualitative research, below are few ethical responsibilities which guided this research:

(a) Honesty

The researcher was honest in data collection and analysis as he did not fabricate, falsify, or misrepresent research data to suit his own objectives.

(b) Objectivity

The researcher was not biased during data collection and analysis,3 and he only collected data that was necessary for each research objective.

(c) Openness

The researcher was open to new ideas and criticism while conducting this research. This was visible during the monthly research presentations with other master's students wherein his research chapters were critically reviewed.

4.7 Study Limitation

The current study aimed to understand factors for groundwater decline problem in Grootfontein aquifer and in so doing, groundwater level data, rainfall and municipal groundwater abstraction data collected for analysis. However, the following imitations were encountered during data collection:

(a) Missing years in groundwater level data

The researcher planned to analyse groundwater level decline trend from the first date of groundwater level monitoring in the study area, which was January 1970 to the current date of groundwater level monitoring of January 2020 to present a complete picture of groundwater level change within the study area. This could not be achieved due to missing years in groundwater level data as identified during data preparation. The researcher therefore decided to reduce the time of analysis to range between January 1980 and January 2020.

(b) Lack of irrigation abstraction data, land-use data, humidity, and temperature data

The study only used bivariate correlation statistical methods in determining the influence of natural and anthropogenic factors on groundwater level fluctuation instead of multivariate correlation due to lack of both natural and anthropogenic data necessary for the analysis.

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Introduction

The previous chapter described the methods that were used to collect and analyse data with the aim of addressing research questions and achieving the research's objectives set in chapter one. The current chapter presented the analysis results based on the methodologies explained in chapter four. This chapter started by presenting the sample's demographic data to understand the composition and representativeness of the sample. Interpretation and discussion of research results was done in this chapter. A comparative analysis of the results was conducted using similar studies to fully understand the result's implications on the study area. This study analysed and discussed groundwater level fluctuation trends, factors influencing groundwater level fluctuation and presented possible interventions that may be applied in groundwater level decline problem.

5.2 Description of main data

5.2.1 *Results for analysis of groundwater level fluctuation trend*

This study investigated factors responsible for groundwater level fluctuation in order to design interventions that addresses the problem of declining groundwater levels in aquifers with Grootfontein aquifer used as a case study. The study's first objective was to assess temporal groundwater level fluctuation trend. Groundwater level data from three sample stations (D4N0075, D4N0103 and D4N0105) was analysed to determine temporal groundwater level fluctuation trend in the study area. These three samples represented three groundwater abstraction points in the study area whereby sample D4N0075 and D4N0103 represented the municipal abstraction point 1 and 2 respectively while sample D4N0105 represented the irrigation groundwater abstraction area.

Table 3 provides a statistical description for groundwater level sample data. The length of data for all samples was 41 years as indicated by N on Table 5. D4N0075, D4N0103 and D4N0105 were groundwater level sample stations used in this study. Sample D4N0075 had the shallowest groundwater level as indicated by a minimum level of 3.45 mbgl as compared to the other groundwater level samples while sample D4N0105 had the deepest groundwater level as indicated by a maximum groundwater level of 39.54 mbgl. Mean (average) groundwater levels for each sample was 21.55 mbgl, 20.82 and 30.49 mbgl for sample D4N0075, D4N0103 and D4N0105 respectively. Data for all three groundwater sample stations had a negative skewness and a standard deviation of more than 5 which indicated that the data was highly dispersed from the mean. This data was therefore not normally distributed.

Table 5: Descriptive Statistics for data used for objective 1 to 3

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
D4N0075	41	3.45	35.86	21.5539	8.81938	-.338	.369
D4N0103	41	5.98	31.85	20.8217	7.21712	-.412	.369
D4N0105	41	13.29	39.54	30.4968	6.84754	-1.038	.369
Valid N (listwise)	41						

Data for the three groundwater sample stations was plotted in line graphs to understand the peaks and trend in data. Further analysis was conducted to determine the direction and magnitude of trend using Mann-Kendall and Sen's Slope statistical methods.

Figure 3 to 5 present time series plots for each groundwater sample data.

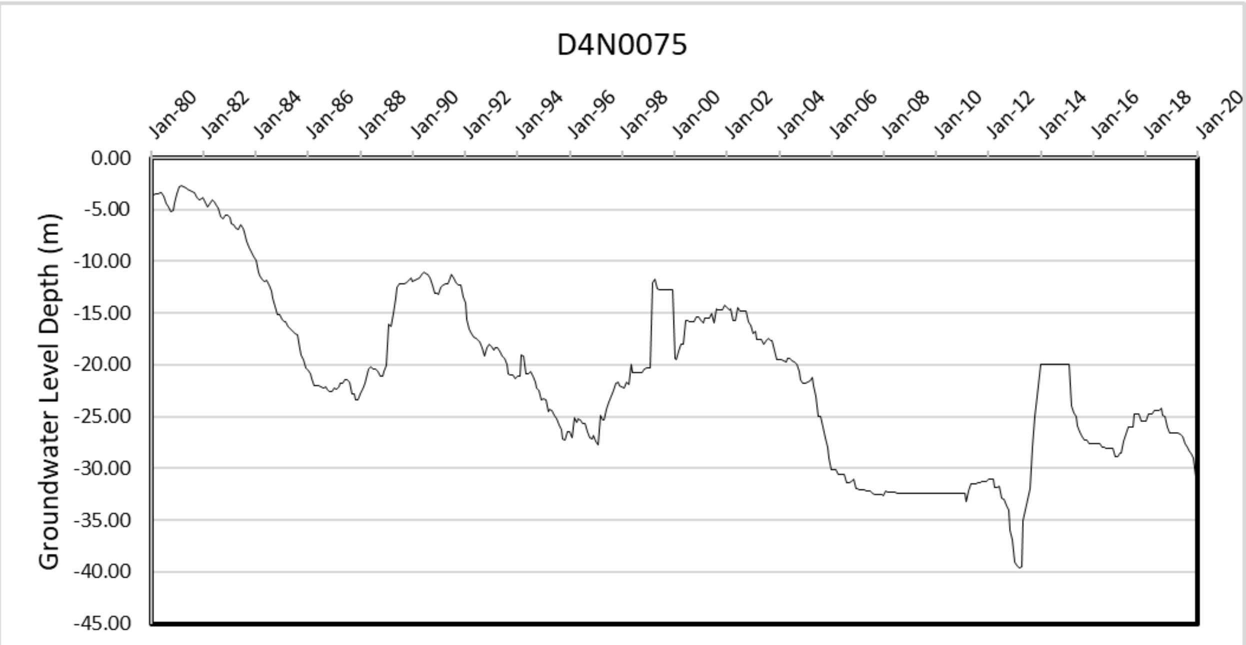

Figure 3: Sample D4N0075 Groundwater Level Fluctuation Time Series

Data for sample D4N0075 as presented in Figure 3 indicated a general 10-year trend of groundwater level fluctuation whereby groundwater level declined from 3.45 mbgl in 1980 to 23 mbgl in 1988 and recovered to around 12 mbgl in 1990, then the decline started again in 1991 to 27 mbgl in 1997 only to recover to around 12 mbgl in the year 2000. Groundwater level did not recover in the year 2010 therefore breaking the 10-year trend.

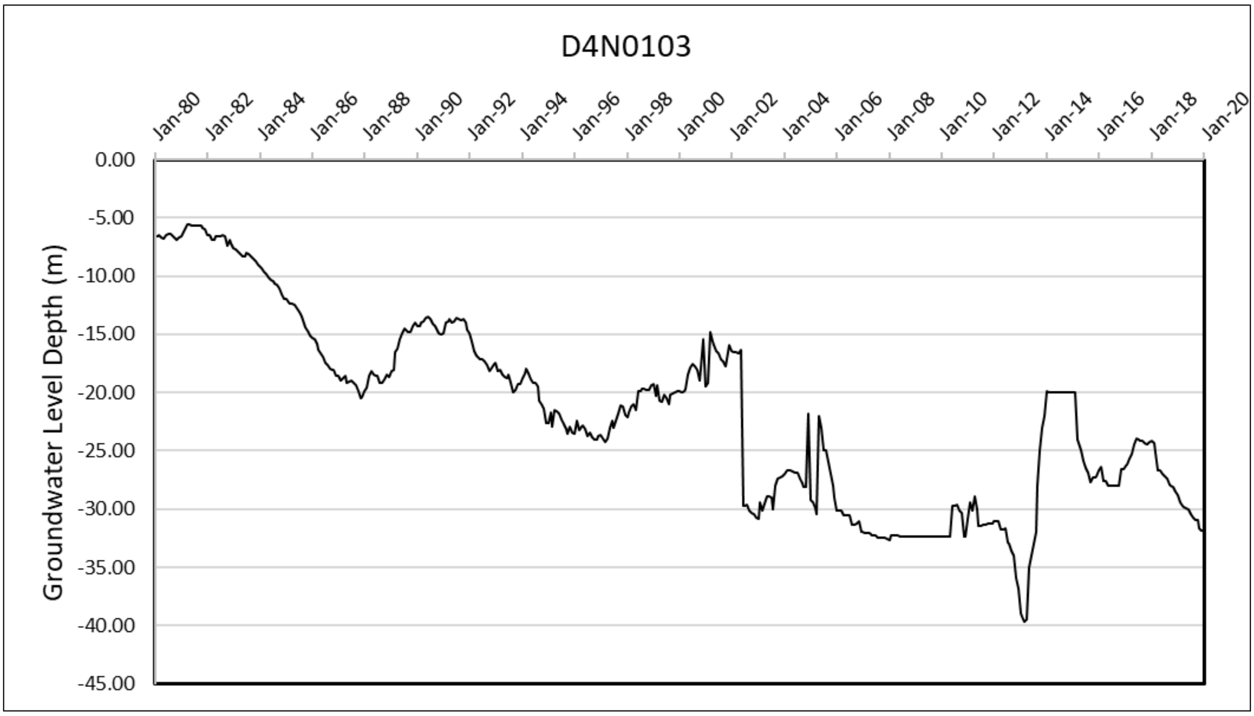

Figure 4: Sample D4N0103 Groundwater Level Fluctuation Time Series

Data for sample D4N0103 as presented in Figure 4 indicated a general 10-year trend of groundwater level fluctuation whereby groundwater level declined from 5.98 mbgl in 1980 to 21 mbgl in 1988 and recovered to around 15 mbgl in 1990, then the decline started again in 1991 to 24 mbgl only to recover to around 15 mbgl in the year 2000. However, groundwater level did not recover in the year 2010 therefore breaking the 10-year trend. Geoundwater level recovery after the year 2000 was below the 15 mbgl as initially observed in the 10-year fluctuation trend.

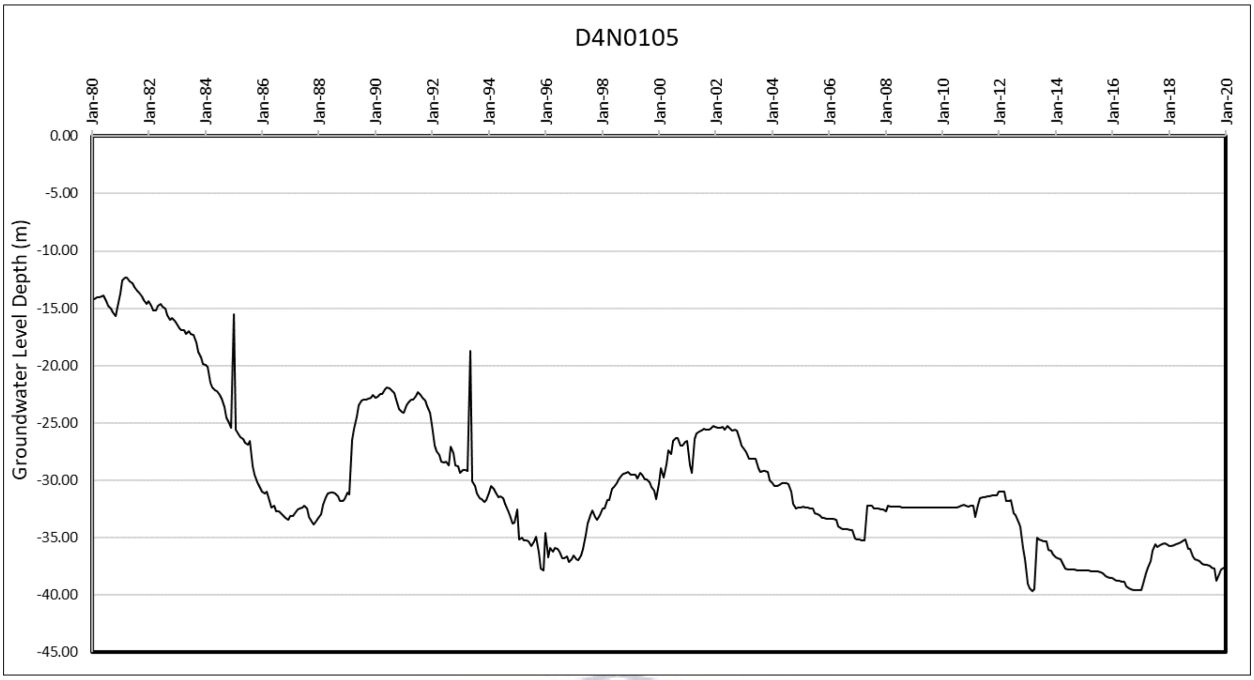

Figure 5: Sample D4N0105 Groundwater Level Fluctuation Time Series

Data for sample D4N0105 as presented in Figure 5 indicated a general 10-year trend of groundwater level fluctuation whereby groundwater level declined from 13.49 mbgl in 1980 to 34 mbgl in 1988 and recovered to around 23 mbgl in 1990, then the decline begins again in 1991 to 37 mbgl only to recover to around 25 mbgl in the year 2000. Groundwater level recovery after the year 2000 followed a 6-year fluctuation trend wherein it recovered to 33 mbgl in 2006 and to 32 mbgl in 2012. No general fluctuation pattern was followed after the year 2013 to 2020.

Table 6 presented a general direction for groundwater level fluctuation for the three sample stations in the study area. All samples had a strong increasing groundwater level declining trend.

Table 6: Mann-Kendall and Sen's Slope Groundwater Fluctuation Trend

Sample ID	MK Value (Z)	Sean's Slop (Q)	Trend
Groundwater Station (D4N0075)	5.28	0.61	Increasing
Groundwater Station (D4N0103)	6.33	0.54	Increasing
Groundwater Station (D4N0105)	5.88	0.48	Increasing

5.2.2 *Results for analysis of influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline*

The second objective was to determine the influence of climatic parameters and anthropogenic factors on groundwater level fluctuation. The main data used for this analysis was the groundwater level data described on Table 5, rainfall data and groundwater abstraction data indicated on Table 7.

Data for both rainfall and municipal groundwater abstraction was indicated on Table 7. The length for all the sample data was 41 years as indicated by N alphabet. The minimum rainfall recorded for the sample station was 292.7 mm while the mean (average) and maximum were 512.76 mm and 873.9 mm respectively. Rainfall data for the sample had a positive skewness and 138.73 standard deviation. Minimum groundwater abstraction for the sample was 2.27 million cubic meters per annum while the maximum and mean annual abstractions were 12.50 and 5.14 million cubic meters respectively. The standard deviation for groundwater abstraction data was 2.81 and was below the mean.

Table 7: Descriptive statistics for rainfall and groundwater abstraction data

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
Rainfall	41	292.7	873.8	512.761	138.7302	.532	.369
Abstraction	41	2.27	12.50	5.1454	2.81805	1.322	.369
Valid N (listwise)	41						

Table 8 to 10 indicated the Spearman correlation (r_s) analysis result between rainfall sample data and groundwater level sample data for the three groundwater abstraction areas within the study area. The length of data was 41 years for both rainfall and groundwater level data.

The result of Spearman correlation (r_s) analysis between Mafikeng WO rainfall data and groundwater level fluctuation for sample D4N0075 was presented on Table 9. The result was (r_s [41]) = -.050, p = .755. The number following the (r_s) in parenthesis corresponds to the sample size while p was the significance level.

Table 8: Mahikeng WO Rainfall Sample Correlation with D4N0075 Groundwater Sample

Correlations

			D4N0075	Rainfall
Spearman's rho	D4N0075	Correlation Coefficient	--	
		Sig. (2-tailed)	.	
		N	41	
	Rainfall	Correlation Coefficient	-.050	--
		Sig. (2-tailed)	.755	.
		N	41	41

Table 9 presented the analysis result for the Spearman correlation (r_s) test between Mafikeng WO rainfall station data and groundwater level fluctuation for sample D4N0103. The result was as follows: (r_s[41]) = -.015, p = .926. The number following the (r_s) in parenthesis corresponds to the sample size while p was the significance level.

Table 9: Mahikeng WO Rainfall Sample Correlation with D4N0103 Groundwater Sample

Correlations

			D4N0103	Rainfall
Spearman's rho	D4N0103	Correlation Coefficient	--	
		Sig. (2-tailed)	.	
		N	41	
	Rainfall	Correlation Coefficient	-.015	--
		Sig. (2-tailed)	.926	.
		N	41	41

Table 10 presented the analysis result for the Spearman correlation test (r_s) between Mafikeng WO rainfall station data and groundwater level fluctuation for sample D4N0105. The result was as follows: (r_s[41]) = -.027, p = .866. The number following the (r_s) in parenthesis corresponds to the sample size while p was the significance level.

Table 10: Mahikeng WO Rainfall Sample Correlation with D4N0105 Groundwater Sample

Correlations

			D4N0105	Rainfall
Spearman's rho	D4N0105	Correlation Coefficient	--	
		Sig. (2-tailed)	.	
		N	41	
	Rainfall	Correlation Coefficient	-.027	--
		Sig. (2-tailed)	.866	.
		N	41	41

Table 11 to 13 indicated the Spearman correlation (r_s) analysis result between municipal groundwater abstraction data and groundwater level fluctuation for the three groundwater abstraction areas within the study area.

Analysis result for the Spearman correlation (r_s) between municipal groundwater abstraction data and groundwater level fluctuation for sample D4N0075 located at municipal abstraction point one, was presented on Table 11. The result was as follows: (r_s[41]) = -.788, $p < .001$. The number following the (r_s) in parenthesis corresponds to the sample size while p was the significance level.

Table 11: Municipal Groundwater Abstraction Data's Correlation with D4N0075 Groundwater Sample

Correlations

			D4N0075	Abstraction
Spearman's rho	D4N0075	Correlation Coefficient	--	
		Sig. (2-tailed)	.	
		N	41	
	Abstraction	Correlation Coefficient	-.788**	--
		Sig. (2-tailed)	.000	.
		N	41	41

**. Correlation is significant at the 0.01 level (2-tailed).

Analysis result for Spearman correlation (r_s) between municipal groundwater abstraction data and groundwater level fluctuation for sample D4N0103 located at the second municipal abstraction point was presented on Table 12. The result was as follows: (r_s[41]) = -.876, p < .001. The number following the (r_s) in parenthesis corresponds to the sample size while p was the significance level.

Table 12: Municipal Groundwater Abstraction Data's Correlation with D4N0103 Groundwater Sample

Correlations

			D4N0103	Abstraction
Spearman's rho	D4N0103	Correlation Coefficient	--	
		Sig. (2-tailed)	.	
		N	41	
	Abstraction	Correlation Coefficient	-.876**	--
		Sig. (2-tailed)	.000	.
		N	41	41

**. Correlation is significant at the 0.01 level (2-tailed).

Analysis result for Spearman correlation (r_s) between municipal groundwater abstraction data and groundwater level fluctuation data for sample D4N0105 located at the irrigation abstraction area was presented on Table 13. The result was as follows: (r_s[41]) = -.832, p < .001. The number following the (r_s) in parenthesis corresponds to the sample size while p was the significance level.

Table 13: Municipal Groundwater Abstraction Data's Correlation with D4N0105 Groundwater Sample

Correlations

			D4N0105	Abstraction
Spearman's rho	D4N0105	Correlation Coefficient	--	
		Sig. (2-tailed)	.	
		N	41	
	Abstraction	Correlation Coefficient	-.832**	--
		Sig. (2-tailed)	.000	.
		N	41	41

***. Correlation is significant at the 0.01 level (2-tailed).*

5.2.3 Result for possible interventions to declining groundwater levels

The third objective was to determine possible interventions for groundwater level decline wherein a trigger level-based groundwater management approach was adopted. In this approach, a certain groundwater level zone was chosen whereby management actions were triggered when that level was exceeded.

The main data used for this objective was the monthly groundwater level data from 1980 to 2020 for the sample station D4N0075, D4N0103 and D4N0105. Data analysis was conducted in Microsoft excel spreadsheet and the result was presented on Figure 6 to 8. Average monthly groundwater level data for the three sample stations was ranked into different percentiles of historical groundwater level zones ranging from the 5th to the 95th percentile zone to determine the trigger-level. A 50th percentile of historical groundwater level zone was chosen as the trigger-level and observed monthly groundwater level data was monitored against the chosen trigger-level zone from October 2018 to December 2019 as indicated by dotted red line.

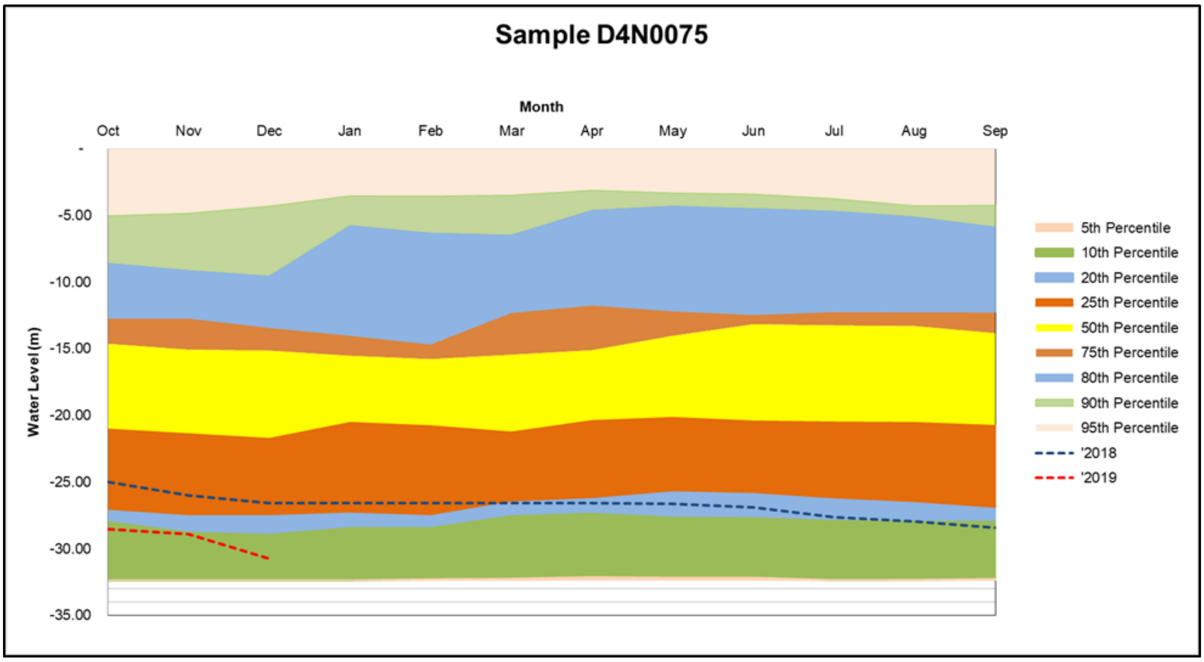

Figure 6: Groundwater Level percentiles for sample D4N0075

Figure 6 presents percentile zones for historical groundwater level and observed monthly groundwater level from 2018 to December 2019 for sample D4N0075. The 5th percentile zone represented shallow historical groundwater level while the 95th percentile zone represented the deepest historical groundwater level which was between 32 and 33 mbgl. The trigger level at 50th percentile zone ranged between 15 mbgl and 21 mbgl. Observed groundwater level from October 2019 to December 2019 was tracking along the 90th percentile zone of groundwater levels as indicated by the red dotted line.

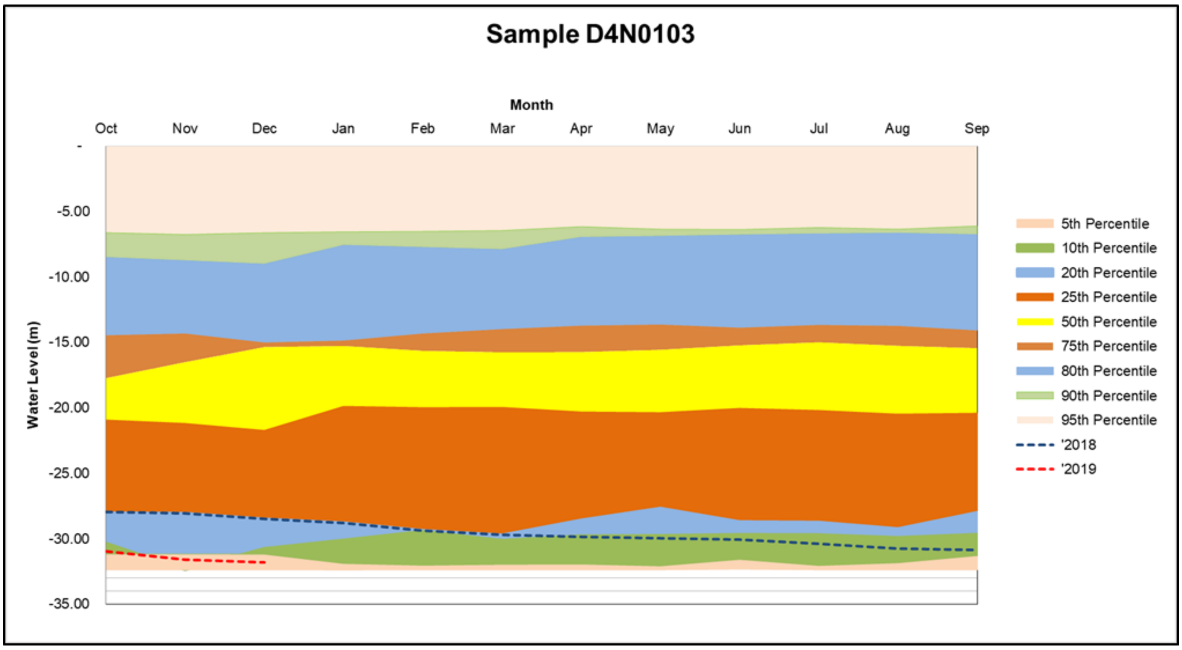

Figure 7: Groundwater Level percentiles for sample D4N0103

Figure 7 presents percentile zones for historical groundwater level and observed monthly groundwater level from October 2018 to December 2019 for sample D4N0103. The 5th percentile zone represented the historical shallow groundwater levels while the 95th percentile zone represented the deepest historical groundwater level which was between 31 and 33 mbgl. The trigger level at 50th percentile zone ranged between 16 mbgl to 23 mbgl. Observed groundwater level for October 2019 to December 2019 was tracking along the 95th percentile zone of groundwater levels as indicated by the red dotted line.

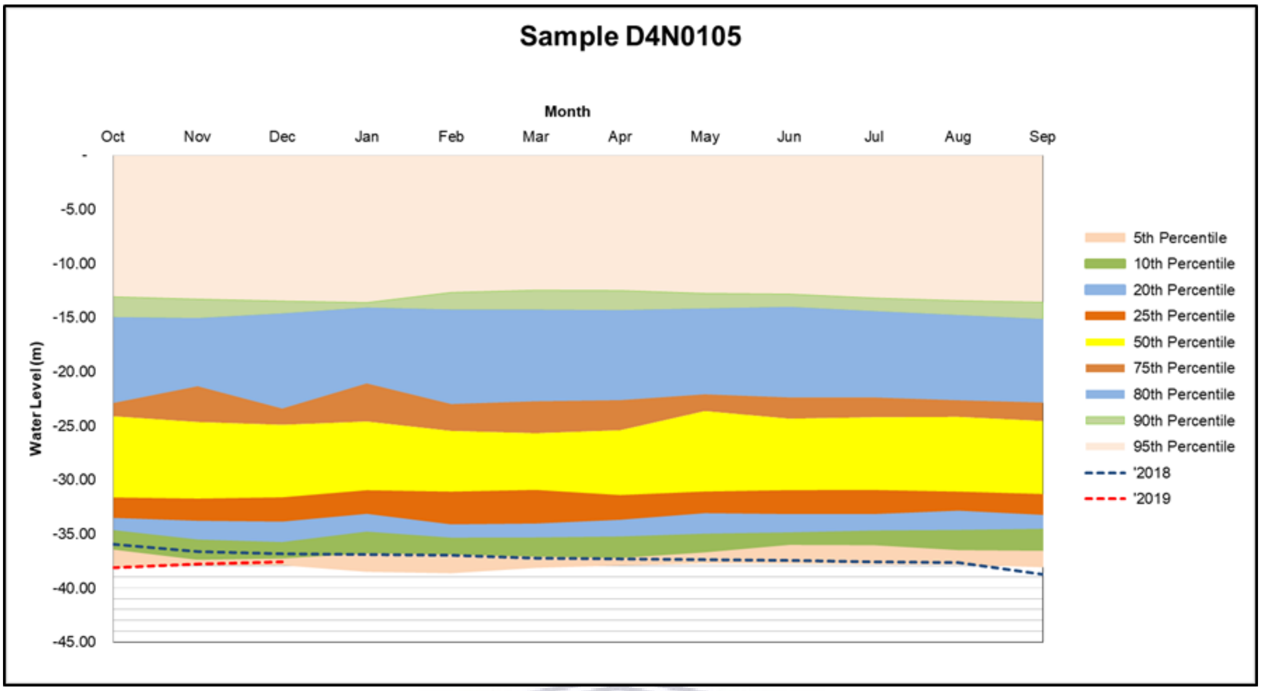

Figure 8: Groundwater Level percentiles for sample D4N0105

Figure 8 presented percentile zones for historical groundwater level and observed monthly groundwater level from October 2018 to December 2019 for sample D4N0105. The 5th percentile zone represented the shallow groundwater levels while 95th percentile zone represented the deepest historical groundwater levels which was between 33 and 37 mbgl. The trigger level at 50th percentile zone ranged between 24 mbgl to 32 mbgl. Observed groundwater level from October 2019 to December 2019 was tracking along the 95th percentile zone as indicated by the red dotted line.

5.3 Computational analysis [Data analysis/statistical analysis]

5.3.1 Descriptive and inferential statistical analysis on temporal groundwater level fluctuation trend

The first objective was to assess temporal groundwater level fluctuation trend within the study area. Time series plots for the three sample stations were indicated on Figure 3 to 5 while the general trend as assessed using Mann-Kendall and Sen's Slope was indicated on Table 6.

Figure 3 indicated groundwater levels fluctuation trend for municipal abstraction point one as represented by groundwater sample D4N07005. The analysis result showed that groundwater used to recover to 12 mbgl during the 10-year fluctuation cycles from the year 1980 to 2000. However, after the decline in the year 2000, groundwater level recovered to 20 mbgl and to 25 mbgl in 2014 and 2018 respectively. This therefore suggest that groundwater level fluctuation in this abstraction point was on a declining trend as also supported by the analysis results in Table 6.

Data for the municipal abstraction point 2 as represented by groundwater level sample D4N0103 in Figure 3 showed a similar declining trend as exhibited in sample D4N07005. Groundwater level declined and recovered to 15 mbgl in 1990 and in year 2000 respectively but this recovery level was not repeated after the year 2000 to 2020. Groundwater level trend in the second municipal abstraction point was also on a declining trend as indicated on Table 6.

Figure 4 indicated groundwater level fluctuation trend for the irrigation abstraction area as represented by sample D4N0105. Groundwater level fluctuation within the irrigation abstraction area also shows a 10-year cycle but unlike the fluctuation cycles in municipal abstraction points, groundwater level recovery was not to a constant level. The data further showed a 6-year fluctuation cycle of decline and recovery from 2006 to 2012. The over-all groundwater level fluctuation trend was declining.

A comparison of groundwater levels within the three abstraction areas showed that irrigation abstraction area had deeper groundwater levels as the starting groundwater level was 13.29 mbgl in 1980 as compared to the two municipal abstraction points' wherein groundwater levels were 3.45 and 5.98 mbgl respectively.

5.3.2 *Descriptive and inferential statistical analysis on the influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline*

The result of the Spearman correlation analysis between Mafikeng WO rainfall data and groundwater sample D4N0075, D4N013 and D4N015 was presented on Table 8 to 10.

The results indicated that there was a very weak negative association/relationship between rainfall and groundwater level fluctuation within all municipal groundwater abstraction points whereby (r_s[41]) = -.050, p = .755 for sample D4N0075 and (r_s[41]) = -.015, p = .926 for sample D4N0103. The result further indicated that there was also a very weak negative association/relationship between rainfall and groundwater level fluctuation within the irrigation area whereby (r_s[41]) = -.027, p = .866 for sample D4N0105.

Table 11 to 13 presented the analysis results for Spearmen correlation between municipal groundwater abstraction data and groundwater level fluctuation for sample D4N0075, D4N013 and D4N015 representing both the municipal groundwater abstraction points and irrigation abstraction area. The results for Spearman correlation between municipal groundwater abstraction data and groundwater level fluctuation at the two municipal groundwater abstraction points indicated that there was a strong negative association/relationship between municipal groundwater abstraction and groundwater level fluctuation whereby (r_s[41]) = -.788, p < .001 for sample D4N0075 and (r_s[41]) = -.876, p < .001 for sample D4N0103. The correlation results also indicated that there was a strong negative association/relationship between municipal groundwater abstraction and groundwater level fluctuation within the irrigation area whereby (r_s[41]) = -.832, p < .001 for sample D4N0105.

5.3.3 *Descriptive and inferential statistical analysis on possible interventions to declining groundwater levels*

The third objective was to determine possible interventions for groundwater level decline wherein a trigger level-based groundwater management approach was adopted. A 50th percentile trigger level was chosen from data of which when exceeded, management actions were triggered in municipal abstraction points and irrigation abstraction area. Sample D4N0075 and D4N0103 represented the groundwater level at municipal abstraction point 1 and 2 respectively while sample D4N0105 represented groundwater level for the irrigation area.

Observed monthly groundwater level from October 2018 to December 2020 for all groundwater sample stations representing groundwater abstraction areas within Grootfontein aquifer showed that observed groundwater levels have exceeded the 50^{th} percentile trigger level. Sample D4N0075 was tracking along the 90^{th} percentile zone of historical groundwater levels while both sample D4N0103 and D4N0105 were tracking along the 95^{th} percentile zone of historical groundwater levels which was the deepest groundwater level recorded in the monitoring boreholes.

5.4 Interpretation of results/Discussion of results

This study aimed at investigating factors responsible for groundwater level fluctuation to design interventions that addresses the problem of declining groundwater levels in aquifers with Grootfontein Aquifer used as a case study. The current study argued that the problem of declining levels in groundwater can be addressed when factors for such a decline are identified and assessed from a solution-based perspective. Based on this assumption, the following were the research questions: 1. what are the critical factors to declining levels of groundwater in an aquifer? 2. What interventions can be designed to address the problem of declining levels of groundwater in the aquifer system? This study was structured around three objectives to address research problem and research questions. This section therefore provides interpretation of results for data analysed while addressing the research objectives.

5.4.1 Interpretation of results on temporal groundwater level fluctuation trend

The first objective was to assess temporal groundwater level fluctuation trends within the study area. The result for this objective were presented on Figure 3 to 5 and Table 6. Figure 2 and 3 indicated analysis result for the two groundwater samples (D4N0075 and D4N0103) within the municipal groundwater abstraction points. Data for these sample stations identified a general 10-year fluctuation trend for groundwater levels from 1980 to 2000. This trend was characterised by groundwater level recovery to stationary levels in 1990 and 2000 wherein the recovery for sample D4N0075 was to 12 mbgl and the recovery for D4N0103 was 15 mbgl in both years. However, from 2001 to 2020, the 10-year trend was not visible in data but only an abrupt decline and recovery characterised by a declining trend. Data analysis for D4N0075 and D4N0103 suggested that municipal groundwater use followed a sustainable pattern between

1980 and 2000 while the abstraction from 2001 to 2020 was unsustainable as groundwater level recovery was minimal. The sustainable water use pattern between 1980 to 2000 further suggest that there might have been a cap in monthly groundwater abstraction by the municipality which could have been due to low growth in demand within that period. However, as the municipality also abstract water from Setumo Dam and Molopo Eye within the study area, there are possibilities that these sources were prioritised for abstractions between 1980 and 2000 due to low demand therefore resulting in sustainable abstractions on Grootfontein boreholes.

Data for groundwater sample station D4N0105 located at irrigation abstraction area indicated a 10-year fluctuation trend from 1980 to 2000, a 6-year fluctuation trend from 2000 to 2012 and an abrupt fluctuation from 2012 to 2020. However, unlike the trend observed in municipal abstraction points, groundwater recovery was decreasing to lower levels at each trend interval. This suggested that groundwater decline continued with less recovery from 1980 to 2020 which could be because of increased groundwater abstraction from 1980 to 2020. However, there was no irrigation water use data available to make a conclusion.

Table 6 data analysis provided general trend direction and magnitude for all the sample stations from 1980 to 2020. The result indicated an increasing positive trend which therefore mean that general groundwater level was on a declining trend in the study area.

5.4.2 *Interpretation of results on the influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline*

The second objective was to determine the influence of climatic parameters and anthropogenic factors on groundwater level fluctuation. Spearman correlation was used to determine the association between climatic parameter (rainfall) and groundwater level fluctuation and between anthropogenic parameter (groundwater abstraction) and groundwater level fluctuation within the three groundwater abstraction areas represented by sample D4N0075, D4N0103 and D4N0105.

The results for correlation analysis between rainfall and groundwater level fluctuation indicated that there was a very weak negative association/relationship between rainfall and groundwater level fluctuation within the municipal groundwater abstraction points and irrigation abstraction area. This result suggested that for every decrease in millimeters of rainfall, groundwater level increased in meters below ground level (mbgl). However, as groundwater level was calculated from the surface, this increase in meters below ground level was therefore a decline in groundwater levels. A very weak negative relationship between rainfall and groundwater level fluctuation suggested that rainfall was not the main driver for groundwater level fluctuation and therefore this fluctuation could mainly be due to another factor or a combination of different factors. The results could further suggest that groundwater recharge in semi-arid areas did not necessarily occur annually but rather occurred when a certain threshold of rainfall depth was exceeded as suggested by van Wyk, *et al*., (2012).

Correlation between groundwater abstraction at municipal abstraction points and groundwater level fluctuation within the study area was analysed. Results indicated that there was a strong negative association/relationship between municipal groundwater abstraction and groundwater level fluctuation within the three groundwater abstraction areas. This result suggested that for every increase in cubic meters of municipal groundwater abstraction, there was increase in groundwater level. However, as mentioned earlier, an increase in groundwater level was an indication for declining groundwater levels in the study area since groundwater level was measured from the surface in meters below ground level. A strong negative correlation suggested that municipal groundwater abstraction was the main driver for groundwater level decline within the study area.

5.4.3 Interpretation of results on possible interventions to declining groundwater levels

The third objective was to determine possible interventions for groundwater level decline wherein a trigger level-based groundwater management approach was adopted. A 50th percentile trigger level was chosen from data of which when exceeded, management actions were triggered in municipal abstraction points and irrigation abstraction area. Data as presented in Figure 6 to 8 showed that the 50th percentile trigger level was exceeded for both municipal groundwater abstraction points and irrigation area within the study area. This result suggested that intervention actions should be activated to prevent further decline of groundwater levels and to ensure groundwater level recovery to the 50th percentile groundwater level zone. Intervention actions may include restrictions on current groundwater use within the study area and monitoring of groundwater level recovery as a result of such intervention action.

5.5 Comparative analysis of the findings

5.5.1 *Comparative assessment of results on temporal groundwater level fluctuation trend*

The analysis result for the assessment of temporal groundwater level fluctuation trend indicated a positive increasing trend in groundwater level which meant that groundwater levels were on a declining trend. Similar result has been reported in many countries for example; Halder *et al*., (2020) reported a declining trend in 60 % of sample data analysed from 1996 to 2018 using Mann-Kendall statistical method. Declining groundwater level trend was also reported for groundwater level data analysed from 2005 to 2014 in Ghana using Mann-Kendall and Sen's Slope (Gibrilla *et al*., 2018). The few examples cited above therefore shows that this study's findings were not isolated but formed part of the expected finding globally.

5.5.2 *Comparative assessment of results on the influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline*

Spearman correlation analysis was conducted to determine the influence of rainfall and municipal groundwater abstraction on groundwater level fluctuation within the study area. The results indicated that changes in rainfall and municipal groundwater abstraction had an influence on groundwater level fluctuation within the study area. However, the results further indicated that there was a very weak negative correlation between rainfall and groundwater level fluctuation and a strong negative correlation between municipal groundwater abstraction and groundwater level fluctuation. The result therefore suggested that while changes in rainfall influenced groundwater level fluctuation, municipal groundwater abstraction was the main driver for groundwater level fluctuation within the study area. Similar results were reported in many parts of the world such Copenhagen, Denmark by Gejl, *et al*., (2019) and Australia by Haas & Birk, (2019) wereby groundwater level declined with the increase in groundwater abstraction. Rainfall was often seen as the most significant driver for groundwater level fluctuation in studies wereby groundwater use data was not analysed such as the study in Southern Laos by Vongphachanh, *et al*., (2017).

5.5.3 *Comparative assessment of results on possible interventions to declining groundwater levels*

The third objective was to determine possible interventions for groundwater level decline wherein a trigger level-based groundwater management approach was adopted. The result indicated that groundwater levels have exceeded the 50th percentile trigger level therefore requiring intervention actions. Literature review on intervention to groundwater level decline was limited. Many similar studies focused on quantifying the effectiveness of both scientific and social interventions (White *et al.*, 2019) to groundwater level decline. Due to this limitation on similar studies, a comparative assessment was not possible, however the result from this study will add knowledge for future studies.

5.6 Implication of the results

5.6.1 *Implication of results on temporal groundwater level fluctuation trend*

The results of assessment of temporal groundwater level fluctuation trends within the study area indicated that groundwater levels for all abstraction areas was on a constant decline with less recovery observed from data. The results therefore implied that the aquifer may be facing imminent risk of groundwater depletion as it was unable to recover.

5.6.2 *Implication of results on the influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline*

The spearman correlation results indicated that rainfall had less influence on groundwater level fluctuation within the study area. The result however, indicated that municipal groundwater abstraction had more influence on groundwater level fluctuation within the study area. This result implied that groundwater levels within the study area may have reached lower levels wherein they are less influenced by rainfall.

5.6.3 *Implication of results on possible interventions to declining groundwater levels*

The result for the third objective indicated that groundwater levels within the study area were within the 90th and 95th percentiles of historical groundwater levels and therefore intervention actions were required. However, as determined in objective two that groundwater levels were less influenced by rainfall, the only interventions required would be on limiting municipal and other groundwater abstractions within the study area.

5.7 Evaluation of the study

The current study aimed at addressing groundwater level decline problem in Grootfontein dolomite aquifer. Three objectives were set to systematically address the research problem and relevant data was collected and analysed for the three objectives. The results confirmed that groundwater level decline problem existed in the study area and also indicated groundwater abstraction as the main factor influencing groundwater level decline. The analysis results also showed that groundwater level decline has exceeded the trigger level percentile zone set in the study therefore requiring that inteveventions actions be implemented to mutigate against further groundwater decline.

This research study had two main strengths. The first strength was the location of research sample stations. Research sample stations were located in all three groundwater abstraction points which enabled the study to conduct analysis of the groundwater level response because of abstraction. The second strength of this study was the adequacy in data collection. This study collected groundwater data and rainfall data with a record length of 40 years which was larger than the minimum expected data frequency of 30-year period acceptable in hydrology (Onyutha, 2016). This data was good in conducting descriptive statistics of the sample and also provided sound statistical significance.

This research study had some limitations. The first limitation was the inadequacy of regional and local literature on groundwater level fluctuation and interventions to groundwater level decline. Inadequcy in literature on this research topic both regionally and locally was attributed to a lack of dedicated groundwater monitoring system in African countries (Gabrilla *et al*., (2018). While this limitation might have hindered the researcher in making important comparisons of this research with other regional studies, this research may be used as a base for future studies to build on.

The second limitation was the small population and sample size. The population size was only limited to 10 participants instead of 29 participants while the study covered an area of 169 km². The small population size was because of lack of data in most groundwater monitoring boreholes in the study area. This small population size influenced the researcher to use non-probability sampling method instead of random sampling methods which were less baised. The small population size also influenced the researcher to use a small sample size of three (3) groundwater monitoring stations which was not representative of the whole study area due to its size. Future studies may test the possibility of generating and using synthetic data from available incomplete data to conduct analysis in the study area.

The third limitation was the use of bivariate correlation ststistics instead of multivariate correlation statistics in determing the influence of climatic parameters and anthropogenic activites on groundwater level fluctuation. Rainfall was the only climatic parameter analysed while other climatic parametes such as humidity, temperature, soil moisture content etc could also influence groundwater level fluctuation. Future studies may add more climatic and anthropogenic variables to be analysed so as to determine their influence on groundwater level fluctuation.

Finally, while correlation analysis were important in determining the relationship and influence of climatic parameters and anthropogenic activites on groundwater level fluctuation, it was important to note that this method did not assure that these relationships weres causative (Schober *et al*., 2018). A cuasative analysis may need to be conducted in future studies to understand the cause for declining groundwater levels and drying boreholes in the study area.

5.8 Summary chapter on results and discussion

Result and discussion chapter presented the analysis results based on research methodologies explained in chapter four. Results were aimed at addressing research questions and the study's objective to provide a solution to the problem of groundwater level decline in the study area. The results were discussed in this chapter to provide a context though which they could be understood in global and local context. This chapter concluded by highlighting the implications of the study's result and linking such results to theory.

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

The previous chapter discussed the analysis findings in relation to the research questions, objectives, and existing literature. The current chapter summarised key findings from research analysis results and addressed the research questions and aims. This chapter outlined the current study's contributions to literature while also discussing the study's limitations and making recommendations for future studies. The current study argued that the problem of declining groundwater levels could be addressed when factors influencing such a decline were identified and assessed from a solution-based perspective. This chapter therefore presented key finding towards solutions to groundwater level decline problem.

6.2 Conclusion and recommendation on temporal groundwater level fluctuation trend

The first objective was to assess temporal groundwater level fluctuation trends within the study area to understand groundwater level decline. Result for this objective showed that groundwater level within municipal and irrigation abstraction areas was on a declining trend from 1980 to 2020. The result further indicated that groundwater levels within the municipal abstraction area recovered to the same level of 12 mbgl between 1980 and 2000 while groundwater levels within irrigation abstraction area recovered but to lower levels at each fluctuation interval. Obtained result therefore showed that groundwater levels within the study area was no longer following any cycle/pattern of decline and recovery but rather on a continuous declining trend. This means that groundwater decline in the study area was irrepressible and therefore it can be said that groundwater availability is threatherned in the study area.

This result should therefore be used to inform both municipal and irrigation users of the critical state of groundwater levels within the study area. The result does not identify possible causes to the observed groundwater level decline trend within these abstraction areas howerer, such information was covered in objective 2. Literature reviewed for this objective was to affirm the methodology used for assessment of groundwater level fluctuation trend and interpretation of findings and conclusion. The literature showed that this objective was achieved.

6.3 Conclusion and recommendation on the influence of climatic parameters and anthropogenic activities on groundwater level fluctuation and decline

The second objective was to determine the influence of climatic parameters and anthropogenic factors on groundwater level fluctuation. Research question for this objective was; what are the critical factors to declining levels of groundwater in an aquifer? The influence of rainfall and groundwater abstraction as the two main factors that influences groundwater level fluctuation was tested. The result indicated that there was a very weak negative correlation between rainfall and groundwater level fluctuation and that there was a strong negative correlation between municipal groundwater abstraction and groundwater level within the study area. A very weak negative correlation between rainfall and groundwater level fluctuation suggested that there was a very small probably of groundwater level decline due the decrease in rainfall and vice versa. This therefore suggested that rainfall was not the main driver for groundwater level fluctuation within the study area. However, the results again indicated a strong negative correlation between municipal groundwater abstraction and groundwater level fluctuation therefore suggesting that municipal groundwater abstraction was the main driver for groundwater level fluctuation within the study area.

The correlation analysis conducted in this study was only bivariate, analysing the association between two variables. The result suggested that rainfall was not the main driver to groundwater level fluctuation, but municipal groundwater abstraction was the main driver for groundwater level fluctuation within the study area. It was recommended that a multivariate correlation analysis be conducted in future as there might be other factors such a humidity, evaporation, rainfall intensity, land use, geology etc. that might also influence groundwater level fluctuation within the study area. Furthermore, a causal analysis may also be conducted to determine the cause of groundwater level fluctuation within the study area as correlation did not guarantee causal relationship. Literature was used to affirm the methodology, interpretation on findings and conclusion and it showed that this objective was achieved.

6.4 Conclusion and recommendation on possible interventions to declining groundwater levels

The third objective was to determine possible interventions for groundwater level decline as a problem identified in the study area. The research question was; what interventions can be designed to address the problem of declining levels of groundwater in the aquifer system? A trigger-level based intervention approach was identified and used to address groundwater level decline problem wherein a 50th percentile of historical groundwater level depth was selected as the trigger-level that required intervention actions when exceeded. Data analysis result indicated that the water level depth in all three groundwater abstraction areas as represented by borehole D4N0075, D4N0103 and D4N0105 required intervention actions as they exceeded the 50th percentile of historical groundwater level depth trigger-level. These actions may include restrictions on current groundwater use within the study area to ensure groundwater level recovery to the 50th percentile of historical groundwater level depth. It was recommended for future studies to scientifically determine the level of restrictions required in the study area for groundwater level to recover to the 50th percentile of historical groundwater level depth. Social studies were also recommended to determine the willingness of stakeholders to implement such restrictions within the study area.

The result from data analysis yielded intended outcomes as the study was conceptualised after an observation of water scarcity due to the reduction in number of abstraction boreholes in the study area. Literature reviewed for this objective was on management and interventions to aquifer groundwater level decline. This literature was used to affirm the methodology, interpretation of findings and conclusion.

6.5 Unanswered question/surprising results

The analysis results indicated that groundwater levels were on a declining trend and that rainfall had less influence on groundwater level fluctuation as compared to municipal groundwater level abstraction. The results for the influence of rainfall on groundwater level fluctuation were surprising as it was expected that rainfall would be a major driver to groundwater level fluctuation. This result therefore left unanswered questions like; was the groundwater in the study area recharged through direct infiltration of lateral recharge?

The results of the analysis also indicated that groundwater levels have exceeded a 50th percentile trigger level and that intervention actions were required to prevent further groundwater level decline. As stated, that groundwater level fluctuation was strongly influenced by municipal groundwater abstraction, it was therefore recommended that restriction levels on groundwater abstraction be determined to restore the aquifer's groundwater level to at least 50th percentile zone of historical groundwater levels at each abstraction area.

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