The use of derivative analysis and aquifer parameter estimation to refine a conceptual model: A case study approach, Western Cape, South Africa

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Declaration

I declare that "*The use of derivative analysis and aquifer parameter estimation to refine conceptual model: A Case study approach, Western Cape, South Africa*" is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete reference.

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Abstract

Hydrogeological characterization of an aquifer system is a first step to determine groundwater quantity, yield potential, socio-economic value, storage capacity and aquifer transmissivity properties of an aquifer as a water resource. Derivative analysis is a technique that has been used to understand groundwater flow systems. This is mainly because derivative analysis of pumping test data and curve matching improves the understanding of aquifer types and hydrogeologic setting of a study site. Time vs drawdown curves produced through pumping tests serve as the most useful tools to analyse aquifer characteristics. The study was conducted through performing pumping test in boreholes of hospital facilities in the Western Cape drilled on the TMG and Malmesbury formation.

Results revealed that analysis from the time versus drawdown derivative plots can be used to determine groundwater flow to wells and boundary conditions within the aquifer to provide understanding and awareness. Furthermore, results validated that time vs drawdown responses allowed characterizing the aquifer types as the analysis results revealed unique responses to pumping. Prolonged operation of boreholes for water supply was established after the interpretation of analysis results. Geological information that was collected during drilling operations, were added to develop an initial conceptual model of the studied groundwater system. A final conceptual model was produced through combination of geological data and pumping test results. This study highlighted that due to complexities resulting to heterogeneous flow in aquifer types, combination of derivative analysis with pumping analytical solutions is essential to improve pumping test data interpretation for prolonged operation of boreholes. This also facilitates the selection of appropriate model that fits the observed drawdown response from an aquifer. In this study, the application of derivative analysis and aquifer parameter estimation is proposed for pumping test analysis to produce a refined conceptual model.

Based on study findings, it is recommended that TMG aquifer should be targeted for groundwater augmentation due to its high depth and bulk water supply. Furthermore, studies on groundwater recharge of the aquifer need to be conducted as it is an important component in aquifer characterisation. Detailed research on groundwater flow system using tracer methods like isotopes and numeric models is essential, more especially on the Malmesbury aquifer. In return, this will assist groundwater managers with informed decision making on groundwater exploration targets.

Keyword

Aquifer characterization

Conceptual model

Groundwater flow

Hydrogeological properties

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Chapter 1: Introduction

This chapter provides the background of the study. It is comprised of the research problem, thesis statement, research question, study aim and objectives. It further presents the significance of the study, conceptualisation of the study, research framework and thesis outline.

1.1 Study overview

This study focuses on hydrogeological characterisation of aquifers to improve the understanding of key hydrogeological features of an aquifer influencing groundwater flow to boreholes. Such features include hydraulic parameters, geological materials, groundwater flow rate and direction, and groundwater units and depths. The study contributes to an enhanced understanding of aquifer characteristics, describing each of the different aquifer systems into detail through conceptual models. Furthermore, this study demonstrates the importance of combining pumping test tools with derivative plots to improve the analysis of pumping test data for detailed characterization of an aquifer and refinement of groundwater conceptual models. Therefore, this study highlights the need for application of derivative analysis approach for full characterization of groundwater flow system in aquifers.

1.2 Background of the study

Groundwater serves as a valuable natural resource for ecosystem, agriculture, domestic and industrial uses throughout the world. This resource is subjected to growing pressure due to climate change, industrial development and increasing population; this is an issue of global concern (Behmel et al., 2016, Ferroud et al., 2019). Effective management of this resource therefore requires full understanding of aquifer characteristics influencing groundwater flow to wells (Tredoux et al., 2009).

Aquifer characterization involves determination of groundwater flow, groundwater productivity and sustainability of aquifers with satellite imagery, pumping tests, geophysics, and modelling (Cao et al., 2013; Ahmed et al., 2018). It is the initial step taken to determine groundwater quantity, yield potential, economic value, storage capacity and transmission properties of an aquifer as a water resource and has always been the main objective to generate sound understanding of a groundwater system by evaluating properties of concern (Kebede 2013; Gomo 2018). This requires collection of precise hydrogeological information and application of conceptual and numeric models to best understand the environment through which groundwater flows, discharges, resides and stored (Manyama et al., 2017). Such information includes subsurface geological characteristics, essential in designing effective groundwater management strategies because groundwater flow and storage is influenced by the geological materials of the subsurface (Shishaye, 2016).

The most common aquifers are fractured aquifers in South Africa, making about 99 percent of all aquifers in the country (Van Bosch 2000). Fractured aquifers such as those comprised of metamorphic rocks are recognised to be highly heterogeneous, complex, non-uniform, and discontinuous due to different degrees of fracturing on the bedrock. This implies that the bedrock transmissivity can vary over the entire bedrock which explains the highly variable well yields in fractured aquifers. Determining a reliable pumping rate which may not deplete aquifers is more challenging because of the extremely complex behaviour of such aquifer systems.

To best understand the groundwater system, development of a hydrogeological conceptual model is essential (Manyama 2017). It is the most basic model defined as a visual representation of how water moves over and through the earth surface and often combines geological and groundwater features, topographical and hydrogeological conditions prevalent in the environment (Prince 2013). Development of a reasonable hydrogeological conceptual model requires understanding and considerations of the discontinuous flow system, anisotropy, heterogeneity, and complexity of the aquifer (Baiocchi et al., 2015). This is imperative for effective groundwater water development as it provides a detailed representation of the groundwater system thus providing sufficient understanding of an aquifer to support decisions affecting the groundwater resource (Wittenberg 2013).

A pumping test is a practical and reliable method of examining aquifer response under controlled condition to abstraction of water to gain information about hydraulic characteristics of aquifer. It is performed by applying stress to the aquifer through pumping and observing the aquifer response in monitoring wells. A pumping test is identified as a useful tool to evaluate groundwater resource potential. It has become the method that yields simultaneous information on the hydraulic behaviour of the borehole, the aquifer's ability to store and transmit water, aquifer extent, presence of boundary conditions and possible hydraulic connection to surface water (Khadri et al., 2016). The pumping test is done with an assumption that if water is pumped from a well, the measured pumping rate and drawdown can be substituted into an appropriate formula to calculate the hydraulic characteristics of the aquifer This procedure requires a pumping well, observation borehole and a monitoring well. (Balasubramanian 2017, Singhal et al. 1999).

Transmissivity (T), storativity (S), and specific yield (Sy) are important parameters to assess groundwater potential through analysis of pumping test data using mathematical modelling or any conventional methods (Khadri et al., 2015; Baiocchi et al., 2015). These aquifer parameters depend on the size, shape, composition, compaction, and thickness of the aquifer geological materials. The aquifer parameters define aquifer characteristics such as the quantity of water that can be abstracted from aquifer and reveals its transmission ability (Camp et al., 2009; Khadri et al., 2016). Using the transmissivity classification by Krasny, transmissivity of an aquifer can be related to its capabilities in terms of groundwater exploitation (Juandi et al., 2017; Gxokwe 2017). Setting limits to the amount of groundwater that can be extracted from an aquifer and avoid exploitation is possible with aquifer parameter estimation results from the pumping test (Juandi et al., 2017). Absence of reliable estimates of aquifer parameters results to inaccurate estimation of resource availability, hence performing a pumping test is important for development of local and regional water plans to predict the future availability of the water resource (Lin et al., 2015). The table below shows the definitions of aquifer parameters.

Table 1.1: Aquifer parameters

Aquifer parameter	**Definition**	**Units**
Specific yield	The volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table.	Dimensionless
Transmissivity	The discharge rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient	m^2/d

During the past few decades, researchers have proposed several different methods to analyse the pumping test data and estimate aquifer parameters, however, appropriate analytical solutions for pumping test data analysis need to be carefully selected to obtain reliable results from the analysis (Theim 1906; Theis 1935; Cooper and Jacob 1946; Hantush and Jacob 1955; Hantush 1960, 1966;

Javandel and Witherspoon 1983; Raj 2001, Renard et al., 2009). Analytical methods involve one of the following: curve matching, finding inflection points and fitting straight lines to pumping test data (Khadri et al., 2016). Curve matching is defined as determination of the best match between observed and theoretical drawdown curves. The method is time consuming and involves errors due to personal decision in terms of the best match between the observed and theoretical curves (Khan, 1982; Singh 2002; Birpinar, 2003; Naderi, 2019). It is therefore important to define the aquifer type, boundary conditions, flow regimes and parts of pumping test data satisfying assumptions based on which the analytical solution was developed. The following table shows various pumping test data analytical solutions with their assumptions and equations.

Table 1.2: Analytical solutions for pumping test data analysis

Analytical solution	**Assumptions**	**Equation**
Theis (confined)	It is assumed that the aquifer is homogeneous, isotropic, confined and is of infinite areal extent with uniform thickness over the area. The potentiometric surface is approximately horizontal before pumping. It is influenced by pumping, well is pumped at the constant rate, well is fully penetrating the entire aquifer thickness and receives water influenced by the test, the water in aquifer is removed instantaneously with decline of head; and there is no delayed yield. The storage coefficient and transmmisivity are independent of time and space during pumping. The flow towards the well is radial and essentially horizontal (Kruseman & Ridder 1994).	$S = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}\,dy$
Hantush (leaky confined)	Assumes that the aquifer is homogenous, isotropic, leaky, fully penetrating with uniform thickness. The aquifer is assumed to have unsteady state of flow and that water is released instantaneously from storage with decline in hydraulic head. Aquitards are assumed to have infinite areal extent and uniform thickness. The aquitards are assumed to be incompressible with vertical flow	$S = \frac{Q}{4\pi T} W\,(u, \frac{r}{L})$

	(Kruseman & Ridder 1994).	
Moench (Unconfined or partially penetrating, fracture flow	Aquifer is assumed to be homogenous, leaky confined, isotropic with uniform thickness. The well is assumed to be fully penetrating. Flow to well is horizontal and water is released from storage with decline in hydraulic head. The aquitards have a uniform thickness, vertical hydraulic conductivity, and storage coefficient (Kruseman & Ridder 1994).	$h_D = \frac{4\pi TQ}{Q}(h_0 - h)$
Cooper Jacob (Confined)	Assumptions of the Cooper Jacob Analysis method are similar those of Theis analytical solution (Meirer et al., 1998). The method requires drawdown versus time data set, pumping rate, steady state flow conditions data set and distance from the pumping well to the observation well and in the case of the analysis for the multiple well tests (Kruseman & Ridder 1994).	$S = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}\,dy$
Thiem	Aquifer is assumed to be homogenous, confined, and isotropic with uniform thickness infinite areal extent. The well is screened over the entire thickness of aquifer. The water removed from storage is discharged instantaneously with decline of head (Thiem 190; Kruseman & Ridder 1994).	$r = \frac{-Qw}{2\pi KDh} \times \ln\frac{r}{R} + h(R)$
Neuman	Assumes that the influence of the unsaturated zone upon drawdown of the aquifer is insignificant, diameter of the pumped and observation wells is small therefore the storage in a well is also negligible. The ratio of the specific yield versus the elastic early-time storativity is greater than 10 (Kruseman & Ridder 1994).	$S_c = \frac{Q}{4\pi KD} W\,(u, u_c)$

The use of drawdown derivative analysis method was identified as an improvement in pumping test interpretation because it displays flow regimes with clear characteristic shapes that would require different plots. Derivative analysis needs to be incorporated on the analysis of pumping test data because it is more sensitive to small variations of drawdown caused by variations in aquifer conditions, changes that are less visible on drawdown plots (Bourdet et al., 1989; Chow, 1952; Yabucchi et al., 2009; Ferroud et al., 2019; Roques et al., 2016; Jia et al., 2016). Furthermore, it is sensitive to flow conditions and small variation of drawdown than conventional log and bilog plots. This makes it possible to detect various non-uniformity, heterogeneity and boundary conditions of an aquifer influencing groundwater flow to wells during pumping (Gringarten 2008; Ferroud et al., 2019). This approach therefore improves the quality of interpretation and estimation of aquifer properties becomes more reliable and accurate (Tongpenyai et al., 1981). Derivative plots also help to evaluate and confirm aquifer type to identify a suitable analytical method for pumping test data interpretation. Pumping test data therefore needs then to be analysed and interpreted using an appropriate analytical solution together with derivative analysis (Ferroud et al., 2019; Rafini et al, 2017).

1.3.1 Problem Statement

Prolonged dry periods subject pressure to groundwater resources because of limited groundwater recharge and this is an issue of global concern (Behmel et al., 2016). This challenge requires understanding of the complex, heterogeneous, non-uniform, and discontinuous nature of aquifer systems where groundwater flows to determine long term reliable yield of boreholes. The analytical solutions commonly used are over simplified making it impossible to realistically represent the complexity of an aquifer system (Odling et al., 2013; Hammond, 2017; Ferroud et al., 2018; Verbovsek 2011). Most hydrogeologists still interpret pumping tests data through curve matching theoretical type curves and end up ignoring the flow regimes really occurring in an aquifer (Ferroud et al., 2018; Kussela-Lahtinen et al., 2003; Marechal et al., 2004; Odling et al., 2013; Verbovsek, 2011; Leveinen, 2000; Audouin et al., 2008). This leads to under or overestimation of aquifer parameters (Hammond 2017, Ferroud et al., 2019). Numerous studies have reported that flow regimes occurring in real aquifers are much more complex than what is modelled by the type of curve fitting method (Ferroud et al., 2018, Kussela-Lahtinen et al., 2003; Marechal et al., 2004; Odling et al., 2013; Verbovsek, 2011; Leveinen, 2000; Audouin et al., 2008). To understand the complexity and heterogeneity of aquifer systems influencing groundwater flow to wells, integrated use of derivative analysis and pumping test analytical solutions is essential to assess the influence of aquifer type and boundary conditions groundwater flow regimes towards groundwater flow to well (Ferroud et al., 2018; Renard et al., 2009; Samani et al., 2006). This allows identification of an appropriate model to use when analysing pumping test data (Ferroud et al., 2018; Renard et al., 2009; Samani et al., 2006). Furthermore, it yields realistic and reliable estimations of aquifer properties parameter thus enabling assessment of long-term operation of boreholes.

1.3.2 Research question

Is derivative analysis and aquifer parameter estimation reliable methods for interpretation of pumping test data to refine a conceptual model?

1.4 Study aim and objectives

The aim of the study is to characterise aquifers using geological information, derivative analysis and pumping test traditional analytical tools to produce a refined hydrogeological conceptual model.

To achieve the above-mentioned study-aim, 4 objectives have been set namely

1. Conceptualize aquifer system using geological information from existing conceptual models
2. Determine aquifer types, flow regimes and boundary conditions using drawdown derivative analysis
3. Estimate aquifer parameters using analytical methods for pumping test data analysis
4. Develop a refined hydrogeological groundwater flow conceptual model

1.5 Significance of the Study

This study is important because it focuses on improving the understanding of hydrogeological properties in complex and heterogeneous aquifer systems with unusual behavioural response to pumping test, thus producing information vital in water resource planning. It provides a certain level of information on hydrogeological properties of aquifers in the case study area, which can be used to make inferences about the general expected aquifer types, important in groundwater resource management and development cases, planning and investigation. Furthermore, hydraulic properties and groundwater flow conceptual models are important for groundwater quantity investigations; hence this information will be very useful for future development and management of aquifers within the selected study sites. It will serve as a hydrogeological reference for future groundwater development within the respective study areas, such as locating new well points for groundwater augmentation.

1.6 Conceptualization of the study

The current study seeks to improve understanding on how groundwater flow to wells is affected by aquifer complexity and heterogeneity during pumping through curve matching and derivative analysis. Derivative analysis has been identified as a tool which can be used to uncover aquifer complexity and heterogeneity, features which cannot be revealed by drawdown versus time graphs alone. A systematic review was used to study the existing hydrogeological conceptual models of the selected study areas to develop initial conceptual models that will explain the hydrogeology of the subsurface. The study followed an experimental research design which involved the use of geological information, pumping test and recovery data (groundwater levels) to achieve objective 1, 2, 3 and 4 of the study. This involved evaluation of aquifer types, identification of analysis method, aquifer parameter estimation and uncovering of aquifer heterogeneity. It was also used to achieve objective 2 namely aquifer parameter estimation. Results from derivative analysis and traditional pumping test analytical solutions will then be used to produce a refined groundwater conceptual model describing how groundwater flow to wells is influenced by aquifer complexity and heterogeneity.

1.7 Research Framework

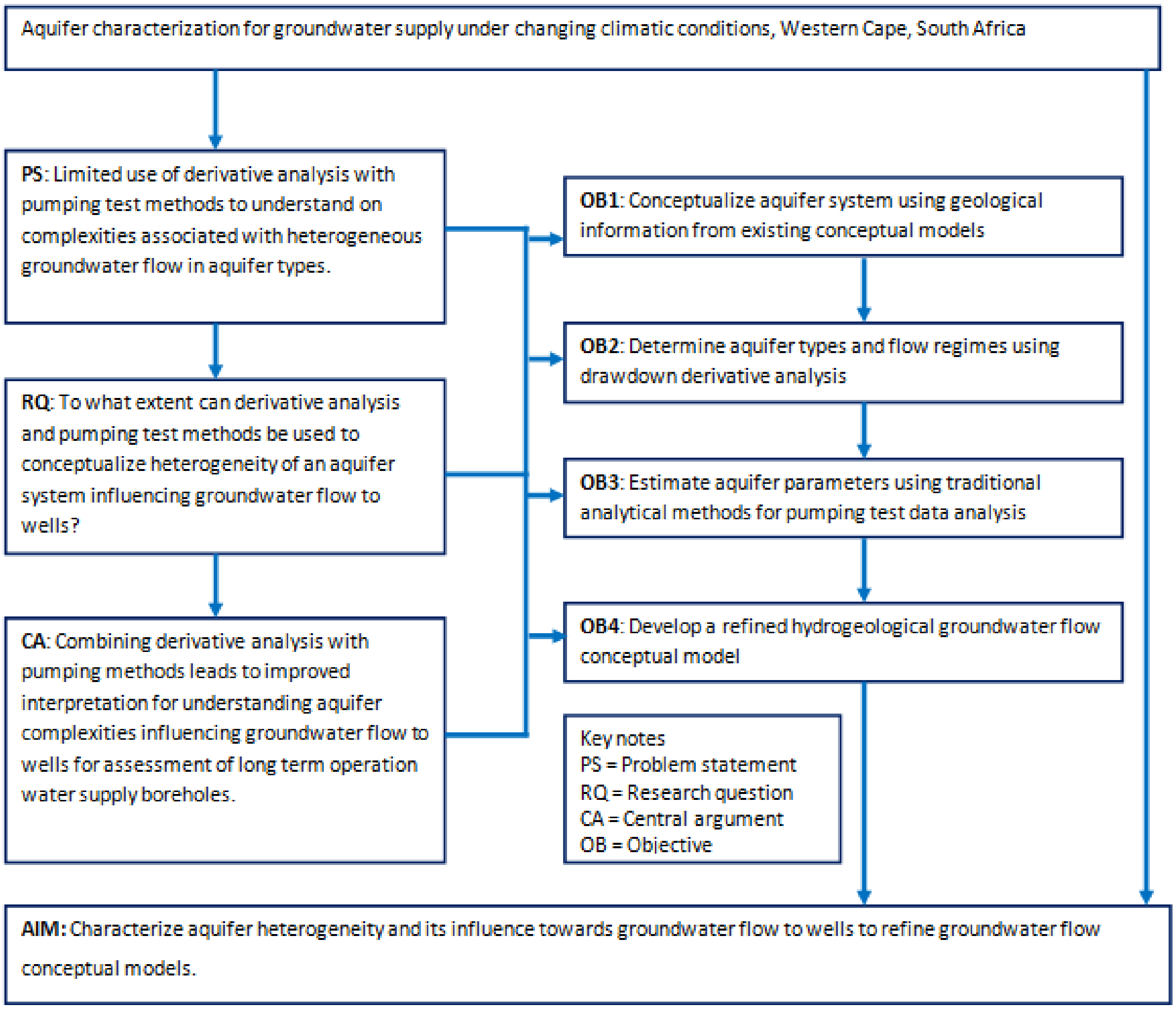


Figure 1: Research Framework

1.8 Thesis outline

This thesis is divided into 5 chapters. Chapter 1 provides a brief background on aquifer characterization and how the study was conceived. It further provides the aim, objectives, research question and the central argument of the study. This study argues that the combination of derivative analysis with pumping test analytical solutions leads to an improved interpretation for understanding aquifer complexities influencing groundwater flow to wells for assessment of long-term operation of boreholes for water supply. The study significance, conceptualization, area description and the research framework are also a component of this chapter. Chapter 2 provides a review of literature and is aimed at revealing the gap in literature with regards to aquifer characterization using derivative analysis for refinement of groundwater flow conceptual models. Furthermore, it consists of local and global studies on aquifer characterization which have been done previously. Chapter 3 provides the research design; study limitations and methodology followed indicating how the study was conducted. Chapter 4 is based on results acquired from data analysis including the initial conceptual model, derivative analysis results, estimated aquifer parameters and the refined groundwater flow conceptual model. This chapter further discusses the results acquired. Chapter 5 presents the conclusion and recommendations based on the findings from the study.

Chapter 2: Literature Review

2.1 Introduction

This chapter presents reviewed information of previous work done in relation to aquifer characterization for groundwater supply. It reviews various studies that have been conducted on a global scale to better understand how aquifer complexity and heterogeneity influences groundwater flow to wells. Furthermore, this was done to improve understanding of hydrogeological properties of aquifers to address the research gap of lack of appropriate knowledge in analysing pumping test data from complex and heterogeneous aquifers with unusual response to pumping test. Aquifer characterization in this chapter refers to distribution of aquifer geometry, hydraulic head, and aquifer hydraulic and geologic properties.

32.2 Review of previous studies

Focusing on conceptualization of an aquifer system, Shishaye et al., (2019) utilized an integrated approach to characterize aquifer and evaluate groundwater productivity in lake Haramaya, Ethiopia. The aim of the study was to highlight the importance of integrating geological, hydrogeological, and geophysical approaches to characterize an aquifer and investigate groundwater productivity. Data from geological maps, drilling logs, pumping test and vertical electrical soundings was used to characterize the aquifer system and produce a 3D hydrogeological conceptual model. Results from geological characterization revealed that the aquifer system is a single, shallow, and unconfined aquifer with a heterogeneous and anisotropic nature and moderate to low productivity range. Pumping test and VES data were used to determine aquifer transmissivity and hydraulic conductivity which were 126.5 ± 25.8 m^2/ day and 4.1 ± 1.0 m/day, respectively. Furthermore, aquifer pumping test results revealed that with the current water use, groundwater level will continue to decline and within 27-32 years, groundwater might not be enough therefore reduction of groundwater extraction by 50 % was recommended. Shishaye et al., (2019) informs the current study that integration of aquifer characterization approaches is essential to reduce uncertainties associated with each method, increase sampling efficiency, and provide a more comprehensive characterization of an aquifer system.

Focusing on derivative analysis of pumping test data, Ferroud et al., (2018) and Rafini et al., (2017) have illustrated the importance of applying derivative plots in pumping test data analysis, to avoid misinterpretation of hydraulic boundaries which could have transpired from the use of drawdown plot approach. These scholars highlighted that an aquifer with inclined substratum or interconnected aquifers produce a linear flow regime followed by a radial flow regime which may be misinterpreted as a no flow boundary. Both aquifers produce a strong decrease of drawdown rate after a long duration of pumping test, and this may be misinterpreted as a constant head boundary. These studies have portrayed the sensitivity of derivative plots which makes the signal more unique and sensitive to hydraulic properties of the pumped aquifer and its boundary conditions.

Hammond et al., (2013) conducted research with the aim of identifying reliable yields for public water supply wells in a fractured rock aquifer in central Maryland USA. Historic aquifer test data of two connected fractured rock aquifers were interpreted by application of derivative analysis and diagnostic plots in New Hampshire, USA. Results from the study demonstrated that pumping tests are affected by changes in flow regimes, dewatering of aquifer and disconnected fractures and changes due to well development. Furthermore, from the diagnostic and derivative plots, it was reported that there is leakage and fractures in aquifer signified by steady drawdown and recovery towards 0 whilst dewatering was signified by peak or constant drawdown on derivative. This study informs the current research that pumping test data is affected by aquifer characteristics such as disconnected fractures and flow regimes hence application of diagnostic and derivative plots is essential to determine the correct model to be applied to pumping test data. From the study, it was concluded that to protect yields, it is suggested that water levels should not drop below reservoir units in those types of wells. Furthermore, discharge rate for a long-term pumping test must be chosen carefully because it may be too low so that the drawdown does not reach the permeable units, or too high, such that dewatering is too rapid for the zone to be identified. Reservoir rocks may be better identified by extending the standard three-rate step-test to five or more steps, with progressively increasing discharge rates, while producing the maximum possible controlled drawdown. Hammond et al., (2013) addresses objective 2 of the study focusing on derivative analysis of pumping test data.

Models for pumping test data interpretation were initiated by Thiem (1906) under constant pumping test rate and equilibrium for confined and unconfined aquifers. Since then, various methods have been designed for pumping test data analysis and it is imperative to always note the assumptions for giving analysis. Reliable estimates of aquifer parameters controlling the capacity of aquifer to store and transmit water are acquired through pumping test analysis with analytical models of which Boulton (1954, 1963) Dagan (1967) and Neuman (1972, 1974) are the most popular.

A study by Calvache et al., (2015) highlighted that the first pumping test analytical solutions include the Thiem (1906) applicable in steady state conditions, Theis (1935) and Cooper and Jacob for transient flow conditions. These initial solutions have been modified thus expanding their applicability in various groundwater flow conditions. Modification to the initial solutions formed the Boulton (1954) for delayed drainage in unconfined aquifers, Neuman (1972) for partially penetrating unconfined aquifers, and Hantush (1960) solution applicable in leaky confined aquifers with storage in aquitard. Furthermore, the study investigated the analytical methods to study coastal aquifer properties and discovered that Theis and Cooper Jacob is applicable in coastal aquifers for pumping test data interpretation. Transmissivity and storativity values can be obtained if aquifers are uniform without vertical heterogeneity and without variable density caused by mixing of freshwater and saltwater from ocean. The S and T values obtained were not considered valid and were viewed as approximate and overestimated because the previously mentioned conditions or assumptions were not met. It was highlighted that despite the modifications of the initial analytical solutions, there are still many unresolved limitations that need to be addressed to ensure that reliable information is obtained when interpreting pumping test data. This addresses objective 3 of the study that, analytical solutions to be applied on pumping test data from different borehole sites should be carefully selected by considering the principles, assumptions, and limitations under certain aquifer conditions.

Alexander et al., (2011) used hydrogeological techniques including pumping test analysis and drilling logs to estimate the extent of the hydraulic properties of a heterogeneous aquifer system in Waterloo, Canada. Hydraulic parameters evaluated include the hydraulic conductivity, transmissivity, specific yield, specific storage, and storage coefficient. The study reported that the method was helpful to delineate the distribution of aquifer hydraulic properties in highly heterogeneous fluvial deposits. However, the hydrogeological method relies on the presence of labour intensive and potentially costly wells that are not always available. Alexander et al. (2011) addresses objective 3 of the study focusing on aquifer parameter estimation thus demonstrating that drilling logs and pumping tests can yield reliable results of aquifer parameters from highly heterogeneous and complex aquifer systems.

Lin et al., (2014) also investigated a hydrogeological conceptual model for characterization of a fracture network and groundwater preferential flow path in the TMG of South Africa. The study aim was to provide more detailed information on flow path and dynamics for sustainable use of groundwater in TMG aquifers. Field measurements, geological maps, hydraulic test responses and remotely sensed imagery were used to develop the conceptual model. Results acquired revealed that a dominant number of interconnected fractures form networks considered being a connectivity pattern in the TMG. Furthermore, the connectivity pattern was found to be dependent on the orientation and density of fractures. Only a small portion of the fractures were found to be responsible for flow circulation. It was concluded that the connectivity of fracture networks is common in the TMG sandstones, especially in locations where hard rocks are exposed and not overlain and confined by geological formations. Lin et al., (2004) informs the current study that the TMG aquifer is a fractured rock aquifer with groundwater flow governed by interconnectedness of fractures, thus addressing objective 4 of the study.

Hoppe et al., (2016) estimated aquifer hydraulic parameters using pumping test data from Nairobi semi confined to confined aquifer to determine the vulnerability to heavy abstraction. Pumping test data from 84 boreholes drilled from 250 to 400m depth was analysed using Cooper-Jacob and Theis Recovery analysis methods. Data analysis involved fitting analytical solutions for pumping test to measured pumping test data using AQTESOLV software. Transmissivity values for all wells ranged between 1.11 and 360.58 m^2/ using Cooper and Jacob method, and between 1.289 and 677.81 m^2/d by the Theis method. From the hydraulic parameters estimated, it was discovered that the Nairobi area has a moderately good groundwater potential because of the high transmissivity values, hence the aquifer has high maximum sustainable yields. It was recommended that further groundwater exploration should be done on eastern and southern parts of Nairobi because they had high transmissivity values indicative of maximum sustainable yields. This informs the current study that boreholes drilled in deep semi confined to confined aquifers, with high transmissivity values should be considered as suitable for long term groundwater supply and further groundwater augmentation, thus addressing objective 3 of the study.

Baiocchi et al., (2015) used a multi scale approach to characterise a metamorphic aquifer with the aim of identifying the most appropriate approach for tapping on groundwater in a challenging environment. The study used surface fracture surveys, injection tests, pumping test and a simplified numerical model. Pumping test data was analysed using the leaky and double porosity models. Results showed extreme heterogeneity and lower hydraulic conductivity of geological materials in comparison with the results from the pumping test. Based on Krasny transmissivity classification, the aquifer was identified as not productive and may be of interest for local water supply. From this study, it was concluded that the multi scale approach is reliable for investigating hydraulic heterogeneity of an aquifer system. The study informs the current study that the multi scale approach can be used in the case of hard rock aquifers.

2.3.1 Existing conceptual models for hydrogeological characterization of aquifer systems

Hydrogeological characterization of aquifer systems is imperative as it provides an understanding of the subsurface geological aquifer properties. This can be achieved using different tools depending on the investigation objectives and the available or accessible equipment. Convectional tools and techniques such as outcropping mapping, drilling, coring, and borehole geophysics are commonly used. Drilling of boreholes remains the principal means of geological characterization for most subsurface investigations. Valuable information on physical and chemical properties of the geological material underlying the site can be obtained from visual observations and analysis made on the borehole geological logs. Characteristics such as topographic and surface water properties, aquifer properties and boundaries, groundwater flow directions, aquifer relationships and water balances are summarized and presented on the conceptual model. Such hydrogeological information helps to improve estimation of quantitative aquifer hydraulic parameters and to also develop realistic, qualitative properties for conceptualization of heterogeneous flow conditions in aquifers. This is imperative because aquifer characterization is essential for effective groundwater water development as it provides sufficient understanding of an aquifer or group of aquifers to support decisions affecting the groundwater resource (Wittenberg 2013). Absence of reliable estimates of critical aquifer parameters such as transmissivity (T) and storativity (S) leads to inaccurate estimation of resource availability (Lin et al., 2015).

Characterizing the flow regime and hydrogeological parameters for bedrock aquifer remains a challenge. This is due to the heterogeneous and anisotropic nature of these aquifers across the scale of observation. Zhou et al., (2015) describes groundwater systems as very complex due to spatial variation of geology and involving of different types of flow processes, hence there is a need for simplification of real-world systems. On the other hand, oversimplification may result to a conceptual model lacking information whilst under simplification may be costly. This study suggested that all features relevant to the system must be included and the irrelevant be excluded.

Tartarello et al., (2017) applied geological characterization to characterize underground reservoirs in Sardinia, Italy and produce a conceptual model. Geological information was applied to estimate aquifer parameters and delineate aquifer volumes and boundaries to improve understanding of structural and lithological complexity of the aquifer. From the results, it was revealed that the reservoir is heterogeneous, with dual porosity or highly permeable system represented by matrix and fracture network. It was also identified that metamorphic sandstones and carbonate rocks are overlain by an alluvial plain. Based on the results, a 3-dimensional conceptual model was then developed.

Gomo et al., (2013) developed a preliminary hydrogeological conceptual model for a heterogeneous alluvial aquifer at the Modder River catchment in Bloemfontein. The aim of the study was to develop a preliminary hydrogeoloical conceptual model. This was done using outcrop mapping and analysis of lithological logs which were tested at the lab for hydraulic conductivity using falling head permeameter. Geological logs showed that the alluvial aquifer is comprised of three-layered unconsolidated sediments which include calcrete, clay silt and gravel sand. The unconsolidated sediments were found overlying shale formation where a groundwater discharge zone is located. These logs also revealed that the spatial variation the nature of unconsolidated sediments groundwater flow and occurrence in the aquifer system. Groundwater flows towards the river and this was determined using water level elevation at the site. Gomo et al., (2013) addresses objective 1 of the study. It informs the current study on the usefulness of outcrop mapping and analysis of drilling logs in improving understanding of heterogeneous aquifer lithology and preliminary hydrogeological setting that is important for aquifer testing.

Baker et al., (2012) used the pumping test technique and geological information to conceptualize groundwater flow in a complex and heterogeneous aquifer system, at Federal Superfund in North California. Geological information revealed that the aquifer consists of a complex multizonal system of permeable gravels and sands composed of units from four geologic formations deposited by the ancestral Feather River, Fluvial channel gravels form the principal aquifer zones composed of clay and silt deposits which locally form clay lenses or aquitards. The hydrogeologic investigation revealed that groundwater movement through the aquifer system is governed by large scale heterogeneities. The geometric mean horizontal hydraulic conductivities for channel gravels range between 120 to 530 ft/day. Mean vertical aquitard hydraulic conductivity is 0.07 feet/day and ground water flow is generally southward.

Dewandel et al., (2011) conceptualized geological discontinuity of a weathered granite rock aquifer in Hyderabad, India. The aim of the study was to improve understanding of the geometry and hydrodynamic properties of the aquifer geological discontinuities. This was done through the use hydraulic test, geophysical and pumping test data. The combination of the geophysical and the geological data enabled characterization of both the structure and geological formations and the geometry of the weathering profile at the site. Pumping test data was analysed using the Theis model but the estimated hydraulic parameters were non-realistic and different from the ones obtained in other wells, thus indicating that the wells are in an aquifer poorly connected to a permeable channel. The study concluded that efforts should be made to improve hydrogeological characterization of aquifers through application of the methods used by the study, to ensure maintainable groundwater exploitation.

According to Attandoh et al., (2013) aquifer characterization involves water budget analysis, recharge estimation, and groundwater availability assessment while Peach (2000) states that it can be preliminary or advanced combining basic information on geology with hydraulic characteristics depending on the focus of study. A study by Tooley and Erickson (1996) used the primary approach to characterize aquifers on study site, which later may be used to carry out the advanced characterization. This informs the current study that the focus on aquifer characterization should primarily be on the hydraulic and physical properties including groundwater flows of which will serve as general understanding of the aquifer resource.

Various conventional and unconventional methods to characterize coastal aquifers exist and have been widely applied. Conventional methods include geological mapping, cross-section, drilling, core or well logging, surface, and borehole geophysics, pumping tests and remote sensing including groundwater models (Paillet and Reese, 2000; Lasher, 2011). Unconventional methods include Fluid Electrical Conductivity logging (Tsang and Doughty, 2003). A study by Pailet and Reese (2000) highlighted that the use of a single method does not fully characterize an aquifer; therefore, integration of pumping test, lithologs and geophysical logs is essential to effectively characterize aquifers. Table 2.1 and 2.2 below shows a detailed Litholostratigraphic succession of the Malmesbury group and TMG to understand the geology of both formations to produce reliable results from pumping test data.

2.3.2 Lithostratigraphic succession of the Malmebury Group

Table 2.1: Lithostratigraphy of the Malmesbury Group (Rozendaal et al. 1999; Kisters et al. 2000; Belcher 2003; Conrad et al. 2019)

Group	Subgroup	Formation	Lithology
Malmesbury	Boland	Brandwacht	Greywacke and pelites
		Porteville	Phyllitic shale, schist, fine to medium grained greywacke, limestone, quartzitic sandstone and conglomerate
		Noree	Phyllite, medium grained greywacke, feldspathic quartzites, sericite schists, feldspathic grits and conglomerates and minor impure marly limestones
		Piketberg	Strongly foliated and lineated feldspathic quartzites, greywackes, sericite, schist, felspathic grits, conglomerates, minor impure marly limestone
	Swartland	Franschhoek	Sericitic arenites, feldspathic conglomerate, deformed intermittent shale beds. Chert, dolomite, schists and shale
		Bridgetown	Chert, dolomite and minor schists and shales crosscut by

			mafic dykes
		Moorreesburg	Greywackes and pelites with well laminated quartz-muscovite-biotite-schist
		Klipplaat	Grey to yellowish quartz schist
		Berg River	Mica schists and meta greywackes with impure limestone layers
	Tygerberg	Tygerberg	Fine grained greywackes and immature quartzites

2.3.3 Table 2.2: Lithostratigraphical succession of the TMG (Lin et al., 2007)

Group	Subgroup	Formation	Bed thickness (m)	Maximum thickness (m)	Lithology
		4000			Siltstone, sandstone, shale
Table Mountain	Nardouw	Rietvlei/Baviaanskloof	0.5 - 1	280	Feldspatic quartz arenite
		Skurweberg	1 – 2	390	Quartz arenite
		Goudini	0.3 - 0.5	230	Silty sandstone, siltstone
		Cedarberg	0.1 – 0.3	120	Shale, siltsone
		Pakhuis	variable	40	Diamicite, shale
		Penninsula	1-3	1800	Quartz arenite
		Graafwater	0.1-0.5	420	Impure sandstone, shale
		Piekenierskloof	0.3 – 1.5	900	Quartz arenite, conglomerate, shale
Basement		The basement is comprised of Malmesbury shales, Gamtoos and Kaaimansargillites with metamorphic rocks and cape granite suite.			

2.3.4.1 Hydrogeology of the Table Mountain Group aquifer

The Table Mountain Group serves as a host of the Table Mountain Group aquifer. It occurs within the Western and Eastern Cape Provinces of South Africa, extending from just north of Nieuwoudtville to Cape Agulhas and eastwards to Algoa Bay.

Aston (2007) classified the TMG aquifer as semi confined due to its phreatic and confined nature with impermeable layers in some areas. The aquifer has a large areal extent and great thickness (Duah 2010). It is dominated by brittle, lithified and uniform sequence of quarzitic sandstone, siltstone and sandwiched shale with faults and fractures and a high potential of bulk water supply and a thickness ranging from 900 to 4000 m (Xu et al., 2009).

Xu et al., (2007) divided the TMG aquifers into four main categories based on their geological structures namely, horizontal terrain aquifer system, fold strata aquifer system, fracture zone aquifer system and composite aquifer system.

The TMG aquifer is then further divided into three categories, the deep, shallow, and coastal aquifer system. The deep aquifers in the TMG are derived from sandstones of the Peninsula formation, serving bulk water supply to the Western Cape Province. Several boreholes drilled within this aquifer at a depth between 200 m and 800 m have yielded an excellent water quantity for water supply in the recent years. Due to the shallow nature of these aquifers, extreme withdrawal results to seawater intrusion (Lian et al., 2007).

The Nardouw aquifer consists of the Rietvlei and Skurweberg sub aquifers separated by the Verlorenvalley mini aquitard. The Peninsula aquifer is subdivided into two sub-aquifers, the Plattekloof and Leeukop sub aquifers (Aston 2007). It has a bulk water supply used for farming purposes. The Nardouw Subgroup which hosts the Nardouw aquifer is comprised of silty or shaly interbeds and associated higher feldspar content compared with Peninsula Formation. It is characterised by repeated sandstone-siltstone and thick, cross-bedded quartzitic sandstones.

Shale layers have a great impact on the fracturing and folding style of TMG aquifers thus resulting to large variations in hydraulic conductivity. Clay resulting from chemical weathering of feldspar can clog the secondary groundwater flow paths (fractures) and reduce permeability further. The Nardouw subgroup consists of three sandstone-dominated formations (Malan and Theron, 1989). The lower Goudini Formation has a transitional contact with the underlying Disa member of Cedarberg.

Formation. It is characterised by repeated sandstone-siltstone cyclicity, and reddish-brown weathering due to iron-oxide content. The middle Skurweberg Formation consists of thick, cross-bedded quartzitic sandstones and is a potentially important fractured-rock aquifer.

The Peninsula Formation, hosting the Peninsula aquifer is comprised of quartz arenites with very low primary porosity due to the cementation of individual sand grains. Peninsula aquifer is much thicker with lower shale content thus faults are expected to remain open with increase in depth (Rosewane, 2002). Further reduction of porosity occurred due to low grade metamorphism associated with the Cape Orogeny. However, increased rock induration led to a higher potential for brittle fracturing during deformation, as well as higher fracture frequencies and thus a well-developed secondary porosity, thus serving as the main groundwater storage and flow path. The Peninsula aquifer is therefore highly fractured with lower shale content than the Nardouw aquifer. The flow system is more dynamic with less blocking of permeabilities from weathered shale materials. This aquifer therefore has high storativity values compared to the Nardouw aquifer assumed of 30% reduction in storativity. The Peninsula Aquifer usually outcrops at higher altitudes and is separated from the Nardouw by the Cedarberg Formation, which are TMG window areas. This aquifer receives more precipitation and therefore more direct recharge. On the contrary, the Nardouw aquifer receives less direct recharge (Rosewarne, 2002).

The Cedarberg formation serves as an aquitard with storage but does not transmit large amounts of water. This formation consists of black silty shale at the bottom, with brownish siltsone and fine sandstone at the top. The lithified sandstone and siltstones have zero primary hydraulic conductivity and act as aquitards (Newton et al., 2006). It is exposed within the southwestern Cape and continues along the whole length of the southern Cape Fold Belt. The Cedarberg formation also serves as a confining layer overlying the Peninsula formation and has significant blow out yield of the underlying Peninsula formation when drilled. Numerous springs occur within the Nardouw and Peninsula formation of the Western Cape and are comprised of the barrier from the Cedarberg Formation. The free-flowing artesian nature of the TMG aquifer confirms that the aquifer is confined under positive pressure, and this is due to the presence of the Cedarberg confining layer (Umvoto, 2009).

The TMG rocks represent a multi-porous medium with fractures and matrix forming the main storage or reservoir respectively (Duah, 2010). The fractures act as permeable conduits for rapid groundwater flow while matrix blocks form main storage and unit reservoir. The rock matrix may either be permeable or impermeable with variable fracture scale and is expected to have its own secondary porosity. TMG rocks are therefore considered to form double porosity and fractured rock aquifer systems with variable transmissivity and storativity hence the porosity of this aquifer is categorised as secondary (Duah, 2010). The main groundwater intersections in the TMG Aquifer are commonly at depths >100 m below ground surface.

Different boundary conditions within this aquifer system are controlled by lithology, geomorphology, and structural discontinuities such as local and regional fault systems. The presence of numerous geological features such as fractures, folds, faults, fissures, and joint systems gives rise to many springs within the TMG Formation (Meyer, 2002). Meyer (2002) divided these springs into three categories based on the mode of occurrence namely lithology-controlled springs, fault-controlled springs, and shallow circulating springs. Lithology controlled springs occur due to the presence of impervious layers, fault-controlled springs are high yielding and occur due to the presence of fractures and are indicative of a deep fracturing system. Example of these springs includes the Caledon thermal spring with a yield of 9 *l/s*.

2.3.4.2 Hydrogeology of the Malmesbury aquifer

The Malmesbury Group forms part of the Western branch of the Saldania belt which consists mainly of metasedimentary and metavolcanic rocks. It serves as a host to a shallow and semi-confined aquifer with an upward flow gradient which prevents downward movement of potential contaminants.

Meyer (2011) discovered that groundwater exploration in the Malmesbury Group is often problematic due to poor exposure, the largely argillaceous and incompetent nature of many of the lithological units and the overall structural complexities. This formation therefore has been overlooked as a usable groundwater source due to its formerly generalised low yields of <0.5 l/s found in the weathered sedimentary and meta-sedimentary rocks. It has been considered as an aquiclude at a regional scale, comprised dominantly of the slates and phyllites considered to be incapable of supporting below the weathered zone of the formation (DWAF, 2008).

An investigation by Conrad et al., (2019) revealed that the Malmesbury Group could serve as a host to high yielding aquifer with a moderate groundwater quality. Results from the study demonstrated that the aquifer is in fact favourable aquifer in certain areas with high aquifer yields and favourable water quality. Areas such as Paarl had borehole yields of up to 21 l/s and it was assumed that the high yields were due to the high yielding brecciated and transmissive fault zones and fractures in the bedrock (Conrad et al., 2019). It has been discovered that the high yields within the aquifer occurred in boreholes drilled along fault related fractures zones at or near the Wellington-Pikketberg fault and shear zone. This fault system has been mapped to end South of into the Wemmershoek and Klein Drakenstein mountains, it continues past Paarl towards Franshoek in the 1: 25000 geological maps correlating to the high yielding boreholes studied. Boreholes that did not intersect these fractures had yields like the previous Malmesbury Group generalisations of <0.5 l/s. This agrees with the research by Umvotho (2018) which discovered that high yields particularly occur where fracture or fault systems are well developed. In such geological settings, borehole yields from these groups can be about 5 l/s and higher whilst the average borehole yields are lower.

Some boreholes drilled into Malmesbury Group shales are likely to receive recharge via the Berg River and associated saturated alluvium, as well as intersecting higher yielding fractures at depth (DWAF 2008). Groundwater recharge also occurs directly precipitation in areas immediately surrounding faults. This may be a concern for long sustainability of the aquifer system if the fracture networks are depleted faster than the recharge to these systems (Conrad et al., 2019).

Groundwater flow within the Malmesbury Group aquifer occurs through fractures and faults. The predominant direction of fault is northwest to southeast. Groundwater flow in the high yielding zones occurs through fault related damage zones with a magnitude greater than what is normally abstract-able from areas with minor fracturing and faulting of geological materials.

2.4.2 Confined aquifer

In a confined aquifer assuming a fully penetrating, homogeneous, isotropic well with small diameter and wellbore storage, the drawdown follows the Theis curve. When viewing the semi-log plot, the drawdown derivative curve portrays a nonlinear relationship at early pumping time but late a 1:1 slope is attained as the curve flattens at late time indicating infinite acting radial flow (Kruseman and de Riddler, 1990). Figure 2.1 shows the typical diagnostic plots that are encountered in hydrogeology from different aquifer types. Diagnostic plot that typically represents a confined aquifer is shown is represented by figure 2.1 (a).

2.4.3 Unconfined aquifer

Curves for the unconfined aquifers demonstrate delayed yield and the log-log plot follows the Theis curve at early times of pumping. The derivative curve flattens during mid time of pumping thus representing recharge from an overlying aquifer, less permeable aquifer which stabilizes the drawdown. The curve again follows a portion of the Theis curve at later times of pumping. The semi log plot is more distinctive and characteristic as it shows parallel straight-line segments at early and late pumping times (Kruseman and de Riddler, 2019). This is presented in figure 2. 1(b) below.

2.4.4 Leaky

In a leaky aquifer, the derivative curve follows the Theis curve during early times. Water is withdrawn from leakage through the aquitard and flow to well reach a steady state at later pumping time, therefore the drawdown in the aquifer stabilizes as shown in figure 2.1 (e) below.

2.4.5 Confined aquifer with recharge boundary

The recharge boundary is characterized by the stabilization of drawdown in the well at late time. The derivative curve departs more and more from the theoretical Theis curve and plunges towards zero at late time. The flattening of the derivative curve at intermediate time is an indication of infinite acting radial flow regime as represented in figure 2.1 (d) below.

2.4.6 Confined closed aquifer

Figure 2.1 (c) shows a derivative plot in a confined aquifer assumes a partially penetrating line source pumping well and closed aquifer with impermeable walls. The derivative curve reaches a plateau at mid time thus indicating infinite radial flow conditions. The drawdown and derivative curve portray a 1:1 slope at late time, indicating a pseudo-steady-state flow regime.

2.4.7 Double porosity aquifer

In this case, a fractured reservoir consists of the matrix and the fractures, which can be represented by an equivalent homogeneous dual porosity system (Warren and Root 1963). The derivative assumes partially penetrating, line source pumping well and fracture. The theoretical curve is quite like that portrayed by an unconfined aquifer, illustrating delayed yield. Aquifer has two systems including the matrix blocks of low permeability and high storage capacity with fractures of high permeability and low storage capacity. Flow towards the well occurs in a radial fashion and unsteady state. The aquifer has three characteristic components on the drawdown-derivative curve. All flow is derived from storage in fractures during early time of pumping. The transition occurs during mid time when matrix blocks feed water at an increasing rate to fractures resulting to a partially stabilized drawdown. The pumped water is then derived from storage in both the fractures and matrix blocks during late time of pumping (Kruseman and de Riddler, 1990). This is shown in figure 2.1 (b) below.

2.4.8 Barrier Boundary

Figure 2.1 (c) represents a cone of depression reaching a barrier boundary results to doubling of the drawdown. It is portrayed by steepening and deviating upward of field data from the theoretical Theis curve and the flattening of the first derivative indicates infinite radial flow conditions. The flattening of the second derivative is an indication of the barrier boundary with twice the slope of the infinite acting period of radial flow. The effect of a recharge boundary is therefore opposite to that of a barrier boundary.

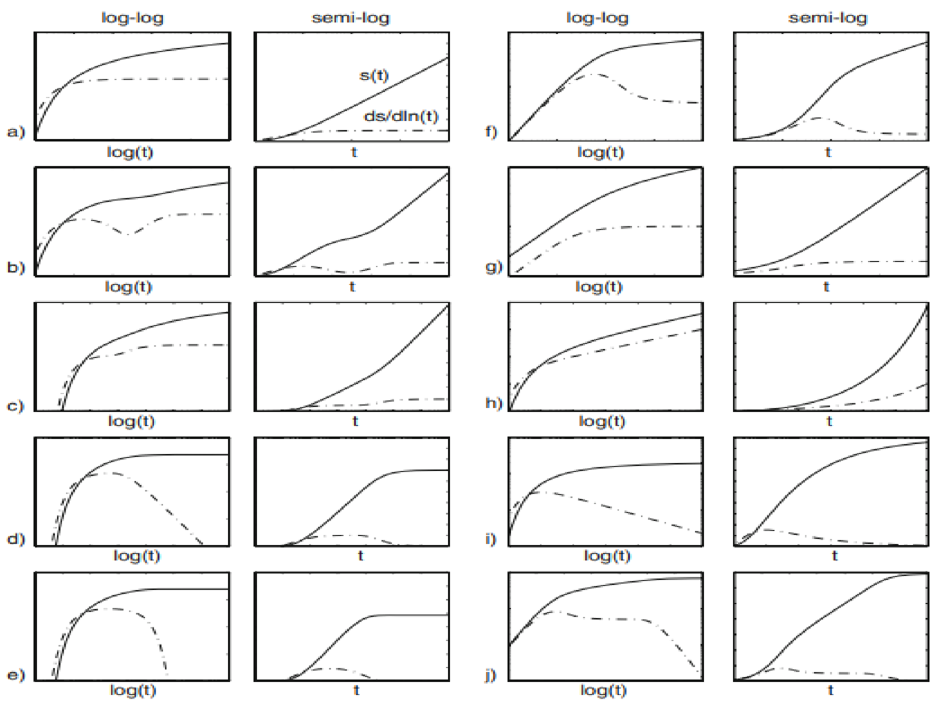


Figure 2.1: Typical diagnostic plots encountered in hydrogeology (Renard et al. 2009)

2.4.9 Case studies on the use of derivative analysis

Choosing an appropriate model which could fit the observed pumping data is an imperative process during pumping test data analysis. It is important to define the aquifer type and parts of pumping test data satisfying assumptions based on which the analytical solution was developed. This requires application of derivative plots to identify and confirm aquifer type to identify a suitable analytical method to be used to interpret pumping test data.

Conducting a proper aquifer pumping test data interpretation to select or refine a conceptual model requires a comprehensive approach in which the derivative response is analysed with respect to the geological conditions of the aquifer. This therefore requires field knowledge such as hydrogeology of the site typically from geological or geophysical surface or log surveys. This permits assessment of the influence of well-bore storage, type of aquifer, presence of boundaries (barrier or recharge boundary), and flow regimes in the pumping test data, dominating at different times during the pumping test (Hammond et al., 2017). Wellbore storage effect is found to be important during pumping tests in hard rock aquifers with low permeability, therefore it needs to be considered. This requires application of a radial flow (slope is usually 0) model which yields reliable estimation of aquifer parameters (Kruseman and de Riddler, 1990).

Several researchers such as Bourdet et al., (1983), Horne (1995), and Bourdet (2002) have proposed interpretation of pumping tests using time derivative of the drawdown curve. This approach is sensitive to identifying effects caused by inner boundary conditions such as skin effect, wellbore storage and well inefficiencies, outer boundaries such as inflow, no flow and establishment of various regimes of flow including radial flow conditions. The interpretation of the drawdown log-derivative signal has the advantage of being much more sensitive to small variations of drawdown. The drawdown log-derivative signal makes it possible to detect various non-uniformity, heterogeneity and/or boundaries in aquifers (Gringarten 2008). Furthermore, diagnostic plots take into consideration the heterogeneity of the aquifers where a formation is affected by discontinuities such as faults, veins, or dykes. Although derivative analysis is considered the best method for identifying an appropriate model for pumping test analysis, it requires many calculations best handled by computer generated algorithms. (Maréchal et al., 2008).

A study by Franke et al., (1987) described the selection of boundary surface and boundary conditions as the most critical step for conceptualizing an aquifer system, therefore incorrect selection of analytical model may result in incorrect modeling of the system. An incorrect model applied bears little information corresponding to real aquifer system response; hence underlying assumptions of models simplifying the actual hydrogeologic conditions and geological and hydrogeological knowledge available for the site needs to be considered to avoid errors.

Renard et al., (2009) interpreted results from diagnostic plots for well test interpretation in a coastal aquifer in Tunisia. Derivative plot results portrayed a Theis similar behaviour initially, stabilization during mid-time and a decrease at late time. Models allowed to interpret such behaviour included a leaky aquifer, aquifer limited by constant head boundary or spherical flow. The constant head boundary was identified as the most suitable model since the well is in close vicinity to the sea. From the results, it was concluded that when there are several models applicable, combining information from different peizometers helps in eliminating some models incoherent to the available information. This informs the current study on how the case of applicability of several analytical solutions for data analysis can be handled.

Moustafa (2011) carried out a study on application of derivative analysis technique for pumping test interpretation in a coastal aquifer. The aquifer studied was classified as leaky and unconfined with no well bore storage. Hantush (1975) and Neuman (1955) methods were suggested as methods for analysis as they deal with no well bore storage. The study confirmed that derivative plots are advantageous as they enable determination of segments of the pumping test data satisfying the assumption of the analytical solution to be used.

McGrail et al., (2012) carried out a study on hydrologic characterization of Wallula basalt pilot well in Washington (USA). From the drawdown derivative plots, it was reported that two flow regimes exist in the aquifer, linear and transitional with a hydrologic boundary condition. Linear and transitional flow regimes were identified from the plots and the causative factors include adjustment of pumping rate and decline in drawdown derivative, respectively. The boundary condition was due to rock leakage and presence of linear constant pressure boundary. This study confirms that some flow regimes detected on the derivative response curve may not be necessarily caused by natural geological conditions of the aquifer but by human interference such as change in pumping rate, hence, the pumping test data should be considered together with the derivative response curve when performing results interpretation.

Rafini et al., (2014) carried out research on the usefulness of drawdown log derivative diagnostic plots in characterizing aquifer heterogeneity for non-Theis aquifers in Maryland (USA). The study reported the aquifer has a conductive fault directly or indirectly proving water to well, this was identified using diagnostic plots since they produce log derivative signatures and flow dimension sequences. Furthermore, the aquifers had variable thickness and partially connected to underlying fractured aquifer, thus producing transient responses. This study informs the current study that recharges barriers and partially connected fractures in an aquifer yield an identical response on the derivative plot.

Xu et al., (2015) carried out a study on diagnostic analysis of artesian aquifers with case studies in the Table Mountain Group of South Africa (Rawsonville and Oudtshoorn). Based on the derivative analysis results from the Rawsonville case, it was reported that a fault core, 80m wide exists and acts as a groundwater barrier and has a significant impact on groundwater flow. It was also reported that there might be more than one flow boundary in the basin, and this was identified from the sharp increase of derivative plot at a later stage. Derivative results from the Oudtshoorn case indicated that the aquifer is homogeneous, infinite, and isotropic at local scale and might have barrier boundary and boundaries at right angles signified by plot deviation, this was identified from early and late portions of the plot. This study informs the current study of the portions and behaviour of the derivative plot that need to be taken into consideration when determining the boundary conditions and geological structures such as faults in an aquifer.

Ferroud et al., (2017) carried out research on pumping well interpretation from flow dimension analysis. From the study, it was reported that in the case of non-radial flow conditions, using the derivative analysis rather than the conventional Theis and Cooper-Jacob methods helps to estimate much more accurately the hydraulic conductivity of the aquifer. It was also reported that the occurrence of both radial and non-radial flow conditions in fractured and granular aquifers indicate the inapplicability of Theis derived models in representing nature.

Rafini et al., (2017) investigated pumping test responses from contiguous aquifers. From the study, it was reported that Theis-derived models are only valid in aquifers with cylindrical-radial flow conditions. Their application to systems with non- cylindrical-radial behaviour may lead to a significant degree of error, leading to a poor understanding of the hydrodynamic behaviour of the aquifer and requiring a substantial degree of approximation when estimating the aquifer's hydraulic properties. This informs the current study that each analytical model is valid in certain flow conditions and this needs to be taken into consideration to avoid misinterpretation of data.

Research by Ferroud et al., (2018) revealed that analysing drawdown-log derivative signals helps improve interpretation of pumping tests by reducing the non-unicity of drawdown signatures. The study highlighted that different flow behaviours can produce the same flow dimension in drawdown vs time graphs. From the study, it was discovered that the same flow dimension value can be observed in various geological settings, such as carbonate rock aquifers, crystalline rock aquifers and alluvial deposits when using drawdown vs time graphs alone. A linear flow regime was observed in both fractured rock and alluvial aquifers. This informs the current study drawdown vs time plots need to be used together with derivative plots to reveal the hidden aquifer characteristics which cannot be determined using drawdown vs time plots alone. Furthermore, derivative plots help to avoid the uniform representation different flow behaviours.

The derivative method has improved diagnostic and quantitative analysis of pumping tests in unconfined aquifers (Karasaki et al., 1988; Ostrowski and Kloska, 1989; Spane and Wurstner, 1993). However, a study by Xiao and Xu (2014) identified the disadvantages of its use in practice. The limitations identified in practice are as follows: Pumping and recovery periods cannot be distinguished in the plots, storativity of pumped aquifers cannot be identified using derivative plots alone, quantitative assessment of double porosity aquifer behaviours cannot be determined using the derivative plots alone and the noise effects cannot be avoided in the derivative calculation process using the differentiation algorithms. Van Tonder et al., (2001) also highlighted that derivative plot can produce plots with artefacts in the shape of common rate derivative due to variation of flow, especially when flow is changing rapidly at the beginning and end of test. This limitation is solved by smoothening raw data prior calculation of the derivative. Furthermore, diagnostic analysis of pumping test data is complex and time-consuming (van Tonder et al., 2001).

A study by Lin et al., (2015) stated that diagnostic plots help identify flow regimes and discern boundary conditions during hydraulic test. Diagnostic plots are not a replacement of conventional methods but facilitate selection of an appropriate analytical method for evaluation of aquifer properties and aids in validating interpretation when the conventional method is applied. The study highlighted there is not a unique model allowing one to describe behaviours observed in the field; moreover, artesian aquifer heterogeneity may influence flow rate during pumping test, a matter which needs to be addressed. This also confirms that combination of conventional pumping test methods and derivative plots helps to avoid misinterpretation of pumping test data which may results to incorrect and misleading conceptual model.

The drop in the derivative curve is caused by fluid flow from the outer porous medium towards the borehole due to large volume of fractures.

2.5 Various aquifer flow regimes revealed by derivative analysis

Linear flow regime

The linear flow regime occurs during early and late time of the derivative curve. Early time linear flow indicates flow of fluid from fractures close the wellbore.

Early bi-linear flow describes simultaneous linear flow of fluid from natural fractures in the drainage area close to the wellbore to the hydraulic fractures and from hydraulic fractures to the horizontal wellbore. It is one dimension flow recognized by slope of ð1=4Þ on pressure derivative curves. It occurs at early time of production. In realistic cases, it cannot be noticed because of wellbore storage effect. This flow regime is controlled by the storativity of natural fractures and hydraulic fracture conductivity.

Late time linear flow portrays fluid flow from the porous medium to fractures and is controlled by the fluid capacitance of the matrix and fractures. It is distinguished by a slope of 0.5 on the derivative curve.

Linear flow indicates fluid flow from inner porous medium to the hydraulic fractures. This flow regime is controlled by the fluid capacitance of the matrix, natural fractures, and hydraulic fractures in addition to the hydraulic fracture conductivity. It is distinguished by slope of ð1=2Þ on dimensionless pressure derivative curves and the pressure values is always twice the pressure derivative value.

2.5 Estimate aquifer parameters

Many studies have applied analytical solutions to estimate aquifer parameters from pumping test data. A study by Park et al., (2012) used Theis solution for a fissured aquifer with freshwater and saltwater. Chachadi and Gawas (2012), Sabtan and Mohanty et al., (2012) and Lee et al., (2014) also applied the Theis solution in detrital coastal aquifers. Mastrocicco et al., (2013) applied the Cooper Jacob method to interpret pumping tests in detrital coastal aquifers. Diamantopoulou and Voudouris (2008) also applied the Theis and the Cooper-Jacob to characterize a multi-layered coastal aquifer.

Zahidet et al., (2018) studied the deep groundwater system through analysis of pumping test data in South-Eastern Bangladesh. The study area extends over six districts of the South-Eastern Bangladesh. The aim of the study was to assess and monitor groundwater potential to improve potable water supply. The study aim was achieved by performing pumping tests at six locations within the study area. Numerical solutions used for analysis were selected based on consideration of assumptions and actual field conditions as suggested by the pattern of aquifer response to pumping. Hantush method for leaky-confined aquifers was used to estimate aquifer parameters. Transmissivity values were calculated between 123 and 3545 m^2/day. Storage coefficient values ranged from 0.000255 to 0.002502. The T values suggested that the aquifer differs in terms of hydraulic conductivity and thickness in different parts of the study area. The S values suggested that the aquifers are confined to leaky confined in nature, except the Cox's with S value of 0.001301, thus suggesting a confined to semi confined aquifer. This study informs the current study that since geological processes do not deposit sediments uniformly, aquifer hydraulic properties at different locations vary. Furthermore, it suggests that average parameter values can be used in cases where aquifer geometry is complicated thus producing a time drawdown curve that can be analysed using different methods.

Alexander et al., (2010) performed research on methods used for hydrogeologic characterization of a heterogeneous aquifer. The aim of the study was to evaluate the commonly used hydrogeologic site characterization methods to accurately describe the distribution of hydraulic properties in a highly heterogeneous aquifer system. This was done to determine if whether the characterization techniques commonly used by hydrogeologist are sufficient in precisely predicting flow through a heterogeneous media. Pumping test, slug test and permeameter techniques were used to estimate aquifer parameters including specific storage and hydraulic conductivity. Pumping test was performed at six zones of the study site and the data was analysed using the Neuman analytical solution, selected because majority of late-time drawdown fall below the Theis (1935) solution which suggests leakage. Variable aquifer parameter values were obtained from the analysis of pumping test data from the different zones within the site. This indicated that the aquifer is heterogeneous, therefore, the Hantush (1960) analysis methods was not suitable as it assumes homogeneity. This study highlighted that applying a simplified analytical method to a complex geological environment yield averaged hydraulic parameters and these parameters vary from point to point. Despite the assumption of simplification, the model was applied because it has been commonly used by researchers (Marechal et al., 2004; Illman 2006; Illman and Neuman 2005; 2003) to interpret pumping test data in strongly heterogeneous media.

Calvache et al., (2015) highlighted that pumping tests in coastal areas are highly complex due to several specific conditions that influence the results. One of these conditions includes the co-existence of freshwater and saltwater resulting to changes in density, and tide-induced head fluctuations can complicate drawdown data interpretation from pumping tests (Trefry and Johnston, 1988; Sakr, 2001). Chen and Jiao (1999) and Chapius et al., (2006) proposed correcting tidal effects in drawdown data for confined aquifers by subtracting the net tidal effects measured before pumping. Ni et al proposed application of the Cooper Jacob method on the rectilinear stretch of the s-log t function because tides cause regular fluctuations in groundwater of the same amplitude.

Cooper Jacob or Theis method, which is restricted to interpretation of the late-time drawdown, has been the focus of several studies. Meier et al. (1980) showed that the Cooper Jacob method leads to a good approximation of transmissivity, and this was confirmed by several other studies including Indelma, 2003; Copty and Findikakis, 2004; Wu et al., 2005). Sachez-Villa et al., (1999) showed analytically that storativity estimated by Cooper Jacob method provides information on flow connectivity which was further investigated by Trichero et al., (2008) and Fernandez et al., (2011). Limitations with the Cooper Jacob's or Theis solution is that it cannot account for aquifer heterogeneity or complexity. Hence Copty et al., (2011) proposed use of the derivative analysis method for parameter estimation from heterogeneous aquifers. Furthermore, it was discovered that time dependant estimates of T provide information about the underlying heterogeneity of aquifers.

Adongo et al., (2017) evaluated borehole performance by identifying borehole yields and transmissivity through pumping test in Tolon and Wa West and Tolon districts of Nothern Ghana. This was performed with the aim of ensuring that domestic and agricultural water supply is enough for the beneficiary communities. Drilling and pumping test data was collected which was then analysed using the Cooper and Jacob analysis method. Semi log graphs with water level were produced from the pumping test data. A best fit line was drawn to derive the change in aquifer storage. The Tolon borehole showed an increase in drawdown as the pumping test continues, thus indicating that the borehole is receiving recharge from surrounding boreholes. The borehole yield of Wa West and Tolon was 1.8 m^3/ h and 1.4 m^3/ h and transmissivity values were 0.5 m^2/ d and 0.8 m^2/d. The T value of the Tolon borehole suggested that the borehole receives recharge from the surrounding boreholes. The T value of the Wa West borehole indicates that the aquifer properties away from the borehole are poorer than those closer to the borehole. From the study, it was concluded that the yield of both boreholes is enough for domestic water supply. This study informs the current study on how aquifer properties such as transmissivity influence the drawdown behaviour during pumping. Furthermore, it informs the study on how Cooper and Jacob analysis method can be applied to estimate borehole yields from a semi-confined aquifer.

Illman*et* et al., (2016) conducted research on estimation of aquifer parameters using long term water supply pumping and injection records. Theis (1935) analytical solution was used to estimate T and S for water supply boreholes. The study discovered that the use of analytical methods yields no solution on aquifer heterogeneity but is computationally efficient and can provide understanding to aquifer pressure responses. The study discovered that even though some aquifers may not satisfy the uniform aquifer thickness assumption of Theis (1935), efficient results may be obtained if the aquifer is laterally extensive throughout the area. It was recommended that heterogeneity of aquifers be determined through numerical modeling which considers complex geometry of aquifers. The good match between numerically simulated and Theis (1935) results revealed that the Theis solution is adequate for pumping test data analysis.

Hino et al., (2015) conducted a comparative study which involved application of both analytical (Cooper Jacob) and numerical methods (Finite Element Method) to obtain the hydrogeological parameters through pumping tests in phreatic and confined aquifers of Tianjin China. Results from analysis using the two approaches revealed that there are hydraulically connected and leaky aquifers within study site. The numerical method obtained more reliable results than the analytical method. It was concluded that the numerical method can be applied to obtain hydrological parameters in aquifers with non-uniform thickness and inconsistent continuity in the horizontal direction, complicated geological conditions with varying layers and very leaky aquifer conditions.

Calvache et al., (2015) evaluated analytical methods to study aquifer properties with pumping tests in coastal aquifers with numerical modelling in the Motril-Salobrena Aquifer. The study applied Theis and Cooper Jacob analytical tools to determine the error of T and S values obtained due to specific characteristics of the coastal aquifer. The reliability of Theis and Cooper Jacob analytical models was evaluated using the Finite Difference Analytical Model. From the results, it was discovered that the Cooper Jacob and Theis analytical tools can be applied in coastal aquifers to interpret pumping tests and obtain T and S values if the aquifers are uniform, with no major heterogeneity, and in a sector without variable density. Furthermore, storativity data cannot be considered valid and the T values should be viewed as over-estimated if Theis and Cooper Jacob methods are applied in stratified aquifers with vertical hydraulic conductivity.

Gomo (2018) conducted a multi well aquifer pumping testing in confined porous aquifers using the Cooper Jacob Method. The study aimed at identifying the effects of using Cooper Jacob to analyse pumping test data. From the study, it was concluded that the true formation transmissivity can only be determined by interpreting the pumping-well drawdown data using the Copper and Jacob (1946) method.

Wen et al., (2010) estimated effective aquifer hydraulic parameters from an aquifer test with multi well observations in Taiwan. Theis solution was used to analyse data from 10 wells on study site. The results obtained showed that the transimissivity values vary with time and the extent of the cone of depression. Additionally, different transmissivity values were obtained from the 10 wells and these results supported the assumption by Wu et al (2005) that aquifers are inherently heterogeneous; therefore, application of the Theis or other analytical solutions requires multiple observation wells and long record of hydrographs to obtain representative aquifer properties.

Mawlood et al., (2016) compared Neuman (1975) and Jacob (1946) application for analysing pumping test data of an unconfined aquifer. The pumping test results were analysed using Neuman graphical solution and Jacob straight line solution through the AQTESOLV and spreadsheet program. Both programs yielded similar results, however different storativity and transmissivity values were obtained from each analytical solution. Results from both methods cleared that, the Jacob solution is more applicable in unconfined aquifers whereas the Neuman method depends on curve matching of which this may produce approximate values in an unconfined aquifer.

2.5.1 Hydraulic parameters of the TMG aquifer

Hydraulic tests are performed using various methods. The commonly used methods include pumping tests, recovery tests, slug tests and bailer test. However, both slug and bailer tests offer point measurements or less spatial coverage of hydraulic properties of the aquifer, and thus fail to explain or reveal both heterogeneity and anisotropy. Pumping tests, however, does offer a representation of a larger area, and in some cases does address issues of heterogeneity (Price, 2013). Stream flow analysis and non-invasive geophysical methods are some of the methods that allow assessment of the aquifer properties (Ballochestani, 2008). These methods, more like pumping tests allow investigation of aquifer properties at large scales (Manyama et al., 2017).

Hydraulic properties of interest are often transmissivity, hydraulic conductivity, borehole yield, specific capacity and storativity referred to as the specific yield and the storage coefficient in unconfined and confined aquifers respectively (Tse and Amadi, 2008; Xu et al., 2009; Price, 2013; Heath, 1983; Freeze and Cherry, 1979). These properties determine the flow of groundwater readily to boreholes (Price, 2013), and thus important attribute of hydrogeological setting of a particular region. As a result, an assessment of the hydrogeological setting aimed at understanding aquifer properties should thus pay attention to various hydraulic properties of the aquifer resource (Manyama et al., 2017).

Investigation of hydraulic parameters such as storativity and transmissivity in the TMG aquifer has been done by various scholars. According to Jia (2007), storativity of a saturated aquifer can be defined as the volume of water that the aquifer releases from storage per unit surface area per unit decline in hydraulic head normal to that surface. In the case of an unconfined aquifer, storativity is the specific yield, defined as the volume of water the aquifer releases from storage per unit surface area of aquifer per unit decline in the water table. The recommended storage coefficient and specific yield range of the confined and unconfined Peninsula aquifer is 10^{-5}-10^{-3} and 5×10^{-3} - 1×10^{-4}respectively. Rosewarne (2002) concluded that a storativity value of 10^{-5} is a fair estimate for bulk storativity of the Nardouw and Peninsula formations. Recommended values are generalised from the previous studies which have not considered the depth effect on the TMG aquifers. A reason for such wide a range of S values may be due to the heterogenic nature of the aquifer beside the impermeable fault (Riemann and Hartnady 2013). No determinate and consistent values of storativity of the TMG aquifers can be concluded and this is still a challenge encountered in regional studies due to the storativity values being scale dependent (Rieman and Hartnady 2013). The TMG rock matrix is expected to have a very low hydraulic conductivity due to the low primary prorosity of TMG rocks; however, the fractured TMG rocks have a high hydraulic conductivity and groundwater storage (Rosewarne 2002). The borehole yields of deep fractured aquifer systems are expected to be very high although this factor depends on openings available in the rock matrix. A good fracture system is expected to yield up to 100 L/s.

According to Jia (2007), the TMG aquifer system is expected to be highly heterogeneous due to the large variation in hydraulic properties of water bearing fractures and rock matrix. The aquifer heterogeneity is believed to have been exacerbated by the folding of rocks of the Cape Supergroup, thus adding heterogeneity and anisotropy of the aquifer system.

According to Xu and Sun (2014), about 30 % of boreholes in the confined aquifer of TMG are artesian in nature. Table 2.3 below presents the suggested storativity values of the TMG aquifer aquifers.

Table 2.3: Suggested storativity values of the TMG aquifers (Jia, 2007)

Aquifer type	**Range**	**Storativity**	
		Specific yield	**Storage co-efficient**
Nardouw aquifer	Low	7.0×10^{-5}	7.0×10^{-6}
	Medium	3.5×10^{-4}	7.0×10^{-5}
	High	3.5×10^{-3}	7.0×10^{-4}
Peninsula	Low	1.0×10^{-4}	1.0×10^{-3}
	Medium	5.0×10^{-4}	1.0×10^{-4}
	High	5.0×10^{-3}	1.0×10^{-3}

Weaver (2000), Hartnady and Hay (2001) and Kotze (2002) support a storativity of 10^{-2}, 10^{-1} and 10^{-2} to 5×10^{-2} respectively.

Transmissivity (T) of a confined aquifer is defined as the product of the hydraulic conductivity and the saturated thickness of the aquifer (D) calculated using the equation K = TD. The hydraulic conductivity is defined as the measure of the formation to transmit water and it depends on the properties of the rock material and the fluid. Coarse grained and well sorted materials have high hydraulic conductivity unlike fine grained materials. In fractured aquifers such as the TMG aquifer, hydraulic conductivity depends on the density, size, and interconnection of fractures. It is expressed using the equation $\mathrm{k} = \frac{ky}{\mu}$ where μ is the fluid viscosity; y is the specific weight expressing the driving force of the fluid. The transmissivity is determined using the pumping test and analytical solution by Thiem for steady state flow and Theis for unsteady state flow. Transmissivity values calculated several authors produced variable values ranging between 9 m^2/day and 400 m^2/day. Variation of the transmmissivity values is due to anisotropic nature of the TMG aquifer. Estimation of the aquifer thickness may be quite challenging if the borehole is not fully penetrating the entire aquifer.

2.6 Theoretical Framework

The theoretical framework guiding this study is that aquifer characterization is imperative to build and improve understanding of groundwater hydrogeological properties. The theory of aquifer characterization applied to this study involves the use of various applicable methods to establish hydrogeological properties of the TMG and Malmesbury aquifer. The theory of gravity-driven basin-scale flow of groundwater flow theory by Toth (2009) was also applied. This theory explains the formation of groundwater flow systems from local to regional flow in large basins. Furthermore, it states that regional flow systems equate with the dimensions of the natural topographic relief having geology as the main actor. This theory has been applied to explain the groundwater flow system of the aquifers selected for this study. Another theory guiding the study is Darcy's law. Darcy's law states that the fluid flow through the porous media is directly proportional to the differences in heights of fluid of the filter bed and inversely proportional to the length of low path (Freeze and Cherry 1979). The amount of flow is directly proportional to hydraulic conductivity which is dependent on the nature of porous medium. The theory of Darcy's law has been applied on this study to explain results on objective 2, 3 of the study focusing on pumping test analysis, aquifer type and groundwater flow regime identification for development of a refined hydrogeological groundwater flow conceptual model for the selected case study sites. Derivative analysis was applied because, theoretically, it is sensitive to small variations of pressure.

2.7 Conceptual Framework

The study is part of the research projects which were initiated to secure groundwater for various uses during the severe 2016-2018 drought conditions experienced by Western Cape. During this period, numerous studies have been done involving identification of groundwater potential zones from high yielding aquifers. This involved drilling of new boreholes to augment water supply in different sectors such as schools and health facilities within the province. None of these studies focused on fully characterizing the aquifer systems to investigate the reliability of the newly drilled boreholes for water supply. This is crucial knowledge and understanding essential to ensure continuous groundwater supply, hence this study was initiated to better understand the complexity and heterogeneity of aquifers where the new boreholes have been drilled. Furthermore, it seeks to understand how groundwater flow to wells is affected by aquifer heterogeneity during pumping through application of derivative analysis which has been identified as a tool which can be used to uncover aquifer heterogeneity, features which cannot be revealed by drawdown versus time graphs alone.

Chapter 3: Research design and methodology

3.1 Introduction

This chapter presents the study area description, research design and methods followed to achieve study objectives. This involves discussion of methods used for collection and analysis of data for aquifer conceptualization, parameter estimation and reliable yield assessment. This study will review the already existing secondary pumping test data; therefore, this chapter entails methods which were followed for data collection and data analysis methods to be used by the current study.

3.2 Research design

The study will follow a quantitative experimental research design. This will involve numerical analysis of data sets to determine aquifer types, groundwater flow regimes, boundary conditions and estimate aquifer parameters. Mathematical models such as Hantush solution will be used for analysis of data to describe and explain the characteristics of aquifers on study site. Figure 3.1 show the study area map.

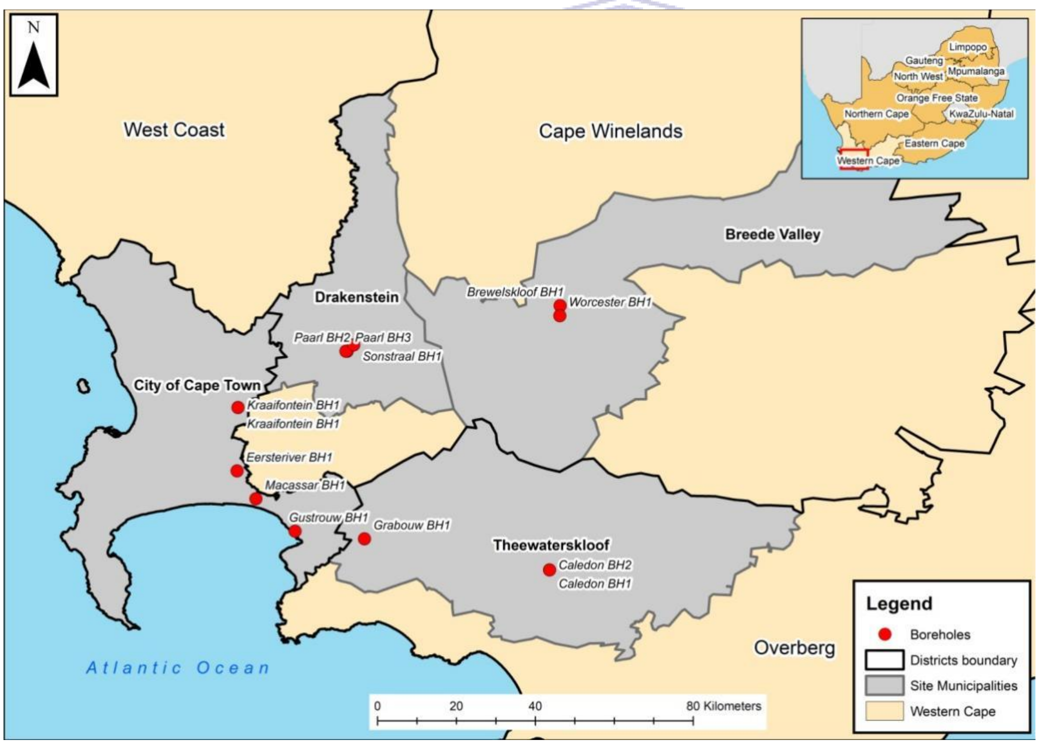


Figure 3.1: Site locality map

3.3 Setting of the study area

3.3.1 Site Selection

The study focused on certain areas within the Western Cape where new boreholes for health facilities have been drilled. Study sites such as Caledon, Sontraal, Paarl, Gustouw, Macassar and Eersterivier were used as a case study to characterize hydrogeological properties of the aquifer system. Areas of interest were selected through desktop study using the 1: 500 000 Geological Map of Cape Town and the 1:500 000 geological map of Worcester. This was done to understand the geology of the subsurface for each of the study sites.

3.3.2 Regional hydrogeological features

Three main aquifer types occur within the Western Cape region. These include the Cape Flats, Table Mountain Group and Malmesbury aquifer. These aquifer systems occur in different geological units, namely the Table Mountain Group, Malmesbury Group, and Cape Granite Suite. The Cape Flats aquifer is an intergranular primary aquifer whilst the TMG and the Malmesbury group are fractured secondary aquifers. The TMG aquifer has been considered as the most favourable target zone for groundwater exploration, however, Conrad et al., (2019) stated that the Malmesbury aquifer is also a high yielding aquifer with favourable groundwater quality; hence it was also utilized as a target zone for groundwater augmentation in hospitals and community health facilities.

The geological materials of the Malmesbury Group are formed by the western branch of the Saldanha belt comprised mainly of meta-sedimentary and meta-volcanic rocks. It is dominantly composed of highly lineated and foliated greywacke, schist, phyllite, shale, conglomerate, and limestone (Belcher, 2003). It is subdivided into three different terrains separated by parallel faults considered to be due to accretionary tectonics. The three terranes include the Boland, Swartland and Tygerberg. Formations within the Boland terrane include Brandwacht, Porteville, Noree and Piketburg. Formations within the Swartland terrane include the Franschhoek, Bridgetown, Moorresburg, Klipplaat, and Berge River. The Tygerbergterrain is formed by the Tygerberg formation. Brandwachct formation is comprised of grewacke and pelites and the Porterville formation is composed of fine to medium quartzitic sandstone. The Noree formation is composed of phyllite, medium grained limestone and dolomite, feldspathic and sericitic quartzite. The Piketberg formation is comprised of strongly foliated and lineated greywackes, conglomerate, feldspathic quartzites, feldspathic grits and minor marly limestones. The Franschhoek formation of the Swartland terrane is comprised of feldspathic and sericitic arenites with feldspathic conglomerates and intermittent shale beds. The Bridgetown formation is comprised of dolomite, minor graphitic schists and shales and the Moorreesburg formation consists of a series of greywacke and well laminated quartz muscocvite biotite schist. The Klipplaat formation is comprised of grey to yellowish quartz whilst the un-metamorphosed Berg River formation is composed of Mica schists and greywackes with limestone layers. The Tygerberg formation is comprised of finely pelitic rocks containing greywackes and immature quartzites. The aquifer is high yielding with a moderate groundwater quality. Structurally, the Malmesbury group is characterized by upright open to tight folding and axial planar cleavage.

3.3.4 Site specific hydrogeological features

The Caledon study site aquifer system is of heterogeneous and anisotropic nature comprised of quartzitic sandstone with intergranular pore spaces intruded by quartz, making rocks to be nearly impermeable (Halbich and Cornell, 1983; De Beer, 2002). Fractures, faults, and folds within this aquifer have developed a fractured aquifer media thus producing secondary porosity where water is stored and flows. The TMG aquifer is considered as a high yielding aquifer (Lasher, 2011). Almost all major wellfields for water supply within the TMG have been developed within the vicinity of fault zones (Kotze, 2002, Hartnady et al., 2012), St Francis Bay (Rosewarne,1993), Ceres (Rosewarne 1993). The steeply dipping fault within the Caledon hospital site is formed by the contact between Gydo and Peninsula formation. It was assumed to be the major water bearing structure because faults within this aquifer have been acknowledged to play a key role in groundwater occurrence in the sandstones. However, this was not the case at the Caledon hospital site because the fault with multiple fractures from the Peninsula formation were not water bearing. The occurrence of a spring nearby the study site implies that there is an impervious clay layer underlying a saturated rock. The spring is the possible source of water recharging the aquifer.

Groundwater at the Paarl site is trapped in pore spaces of unconsolidated alluvium deposits forming the primary aquifer. This formation is underlain by a thick layer of unconsolidated silt and clay mostly dominated by the clayey material. The underlying bedrock is comprised of grey-black consolidated shale of the Malmesbury formation that has been metamorphosed into hornfels. Groundwater is trapped in joints, fissures, and fractures at a depth of approximately 36m of the Malmesbury formation forming the secondary aquifer (Engelsman et al., 2000). Prevailing geology of the study site suggested that the study site has two aquifer types. The aquifer appears to be confined as the main water strike is at the contact zone between shale and clay. During high rainfall events, the overlying permeable sandy soil allows surface water to infiltrate. The unconsolidated silty and clay layer in the subsurface forms a perched water table as the surface water accumulates above the clay layer due to low infiltration capacity. This prevents penetration of the infiltrated water to the secondary aquifer, resulting to water flow towards the Breede River. Groundwater flow occurs in a south easterly direction toward the Breede River.

Hydrogeology of the Sonstraal site comprised of thick unconsolidated silty clay underlain by the hard rock Malmesbury shale acting as transmissive zones facilitating groundwater flow. The aquifer is alluvial with fine unconsolidated particles of silt and clay and larger particles of sand and gravel. A perennial river runs through site suggesting aquifer recharged through surface and groundwater interaction.

Groundwater at the Macassar site is stored in a fractured alluvial aquifer located near the ocean. The aquifer is shallow and unconfined, recharged by rainfall. The aquifer is also comprised of fine unconsolidated particles of silt and clay.

3.3.5 Site specific geological features

The geology of the Gustrouw study site consists of deposits from the Malmesbury Group which formed during the Precambrian period. The site is comprised predominantly of greywacke metamorphosed shale with muddy sands and course sandy loam deposits and clayey loam deposits at the base. Underlying this is the poorly consolidated and weathered rocks of the Malmesbury Group which graded into hard consolidated rocks. Geological structures in proximity to the site include an anticline and fault situated closer to ocean. The regional geological materials of the Malmesbury Group are formed by the western branch of the Saldanha belt comprised mainly of meta-sedimentary and meta-volcanic rocks. It is dominantly composed of highly lineated and foliated greywacke, schist, phyllite, shale, conglomerate and limestone (Belcher, 2003). It is subdivided into three different terrains separated by parallel faults considered to be due to accretionary tectonics. The three terranes include the Boland, Swartland and Tygerberg.

Geological description of the Macassar study site is based on drillings samples and 1: 500 000 Geological Map of Cape Town. The upper most layer is formed by the Springfontein formation with eroded material and unconsolidated fine to medium white sand, clay and calcareous material with commuted shells, pebbles, and shells locally along the beach. Underlying this formation is mostly clay and interstitial sand which could have been formed by weathering of the underlying bedrock of the Malmesbury group shale. The bedrock is comprised of the Malmesbury group rocks with hard shale deposits. These geological units are deposits of the Springfontyn formation comprised of quartzitic sands and decalcified dune sands which dominate in coastal zones.

The Paarl hospital site is overlain by a thin layer of highly weathered unconsolidated fine to medium sand with clay and silt particles which can be categorized as alluvial deposits of the Enon formation. This formation is underlain by a thick layer of unconsolidated silt and clay mostly dominated by the clayey material. The underlying bedrock is comprised of grey-black consolidated shale of the Malmesbury formation that has been metamorphosed into hornfels.

The Sonstraal site geology is comprised of rocks from the Malmesbury formation with the top layer being the thick unconsolidated fine silty clay. These deposits resulted from weathering of granite from the nearby Paarl granite pluton. Underlying the topmost layer at the site is the hard rock Malmesbury shale and larger particles of sand and gravel.

The Caledon study site is comprised of geological materials from the Table Mountain Group. The topmost layer of the site is the whitish-pinkish unconsolidated loamy clay. Underlying this layer is the black unconsolidated silty clay of the Gydo formation and the white consolidated medium grained quartzitic sandstone of the Peninsula formation. The quartzitic sandstone with intergranular pore spaces intruded by quartz resulted into nearly impermeable rocks (Halbich and Cornell, 1983; De Beer, 2002). Geological structures within the site include faults and folds forming a fractured aquifer media. The unconsolidated loamy clay forming an overburden and is underlain by the unconsolidated silty clay of the Gydo formation, also underlain by white consolidated medium grained quartzitic sandstones of the Peninsula formation. Impermeable shale is the dominant geological material within the site. Elevation and geological information of the study sites is presented through elevation and geological maps in figure 3.2 and figure 3.3 respectively.

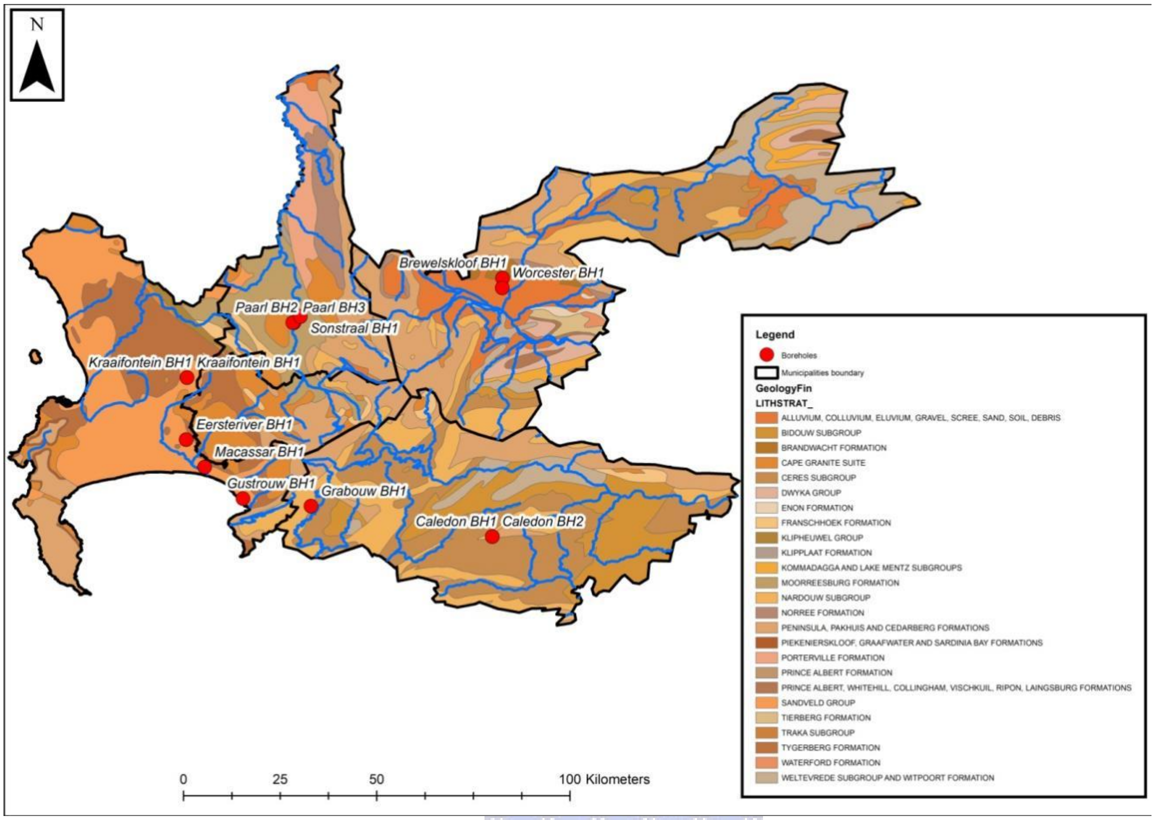


Figure 3.2: Study area geology map

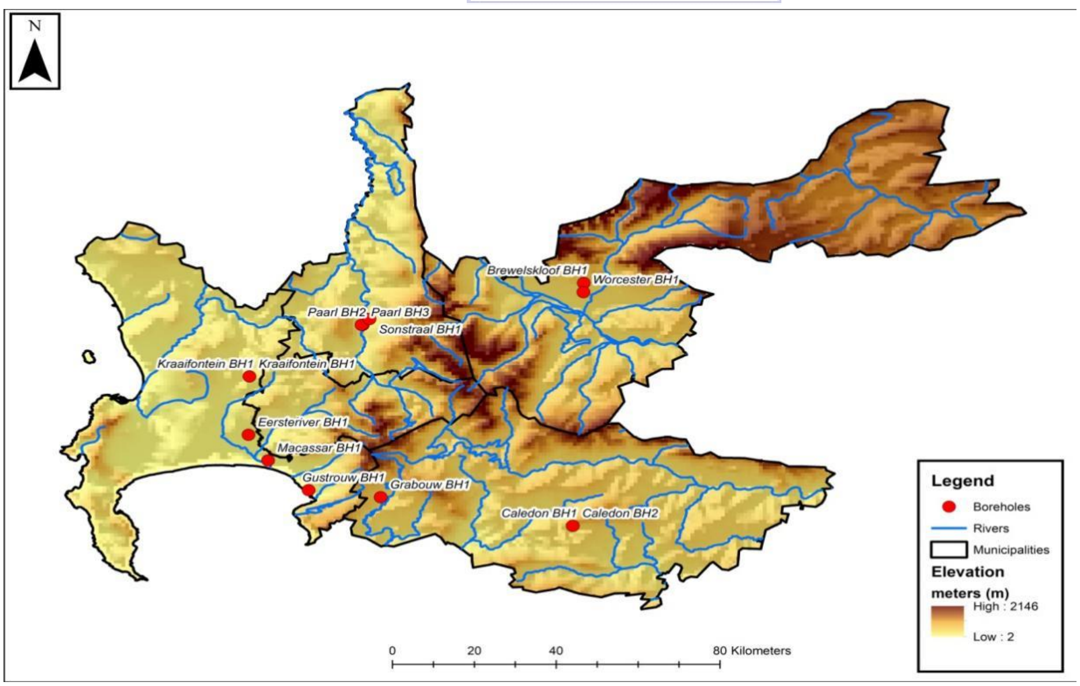


Figure 3.3: Digital Elevation Map

3.3.6 Regional climatic features

The climate of the study area is Mediterranean with cold wet winter and cool dry summer. The annual precipitation within the area varies between 400 and 800 mm (SAWS) while the mean annual temperature is moderate and approximately 17˚C. The region receives most of its rain in the winter months (May-August) with a relatively drier period (<20 mm/month) from November to March. More rainfall occurs in the mountainous area; therefore, the low-lying areas are unable to make use of the available rainfall. There is more rainfall in mountainous areas, as the results many low-lying urban areas are unable to make use of the available high rainfall. Northwest and south-east is the dominant wind direction, furthermore, summer is known with South-easterly (south-east) winds whereas north-westerly winds lead the cold fronts that bring rain to the local area (Atkins, 1970). Climate change results variability in precipitation and extreme weather events, however this has significant effects towards groundwater availability.

3.4 Research Methodology

3.4.1 Data Collection method

The pumping test was conducted in health facilities identified as areas of interest for groundwater exploration to increase water supply. These areas were identified and selected to undergo further investigation through site visits, hydro-census and conducting pumping tests. A desktop study was the first phase of groundwater exploration. This comprised of an investigation of relevant literature such as aerial photography images, regional, local, geological, and hydrogeological maps, and geographical data. Geological data sets collected include borehole log data and geological cross sections of the study area. Hydrological data collected includes production well data, monitoring well data. From the sites identified for groundwater augmentation, six study sites of interest were selected for further groundwater quantity investigation. All boreholes used for well test have variable geometry in terms of depth. The tests conducted include the constant discharge test, step test and recovery test.

The constant rate test was carried out in the study site to acquire information about drawdown and aquifer properties from the specific pumping rate. A step drawdown test was used and was carried out in specific areas within the study area, using single well pumping test approach. The length of test was based on the planned use of the borehole which is water supply to clinics and school facilities. The constant discharge test was conducted for 24 hours to obtain more reliable data. The abstraction rate was constant throughout the duration of the test, and the response of water levels was recorded at certain time intervals (set by SANS 10299-4, 2003). The change in hydraulic head was monitored in terms of drawdown or groundwater elevation changes in aquifer in response to pumping and removal of water from the formation. Variables measured included the static water level, well diameter, distance between pumping and observation well, well location, depth and elevation, discharge rate and depth to water. A dip meter was inserted into the borehole several minutes before pumping commenced to measure the static water level indicated by the sounder probe. This variable will be used to calculate drawdown data during pumping and recovery for each hydraulic test. The aquifer was continuously pumped until equilibrium pumping level was reached. The water level was recorded after every 1-minute interval. The effects of pumping were observed as the water level dropped impulsively. The well diameter, location, depth, elevation, and distance to pumping well were all measured prior pumping of the boreholes. The discharge rate was measured during the pumping period for both hydraulic tests and will be used to estimate T and S of the boreholes. The depth to water level was measured at intervals during pumping and recovery test. This parameter was then used to calculate the drawdown for both hydraulic tests.

The step-down test was carried out to establish the discharge rate to be used for the constant discharge test which will fully stress the aquifer to be used to estimate reliable borehole yield. This was conducted in four steps each encompassing one hour of pumping at a certain constant rate, followed by another one hour at a higher rate till the end of the fourth step. More steps with pumping intervals of up to two hours were done to obtain better data. This was done to disregard the effects of wellbore storage. Rates for different intervals were chosen so that the first step is lower than the required rate, the third step is equal to the expected yield and the final step is higher than that.

The recovery test was performed to determine the natural inflow of groundwater into borehole, with measurements starting at the end of the constant discharge test, when the pump is switched off. The pump was fitted with a non-return valve to ensure that no water enters the borehole from the discharge pipe since this would have influenced the water levels. The water level was continuously monitored until 95% of the drawdown recovered.

3.4.2 Initial conceptual models for groundwater flow system of selected study sites

To achieve objective 1 of the study, records of previous data sets and reports on hydrogeological conceptual models for aquifer characterization were reviewed to obtain the appropriate conceptual model for characterization of aquifers from the different study sites. This information included borehole logs from previous studies and from the specific study sites, well drilling completion reports, geological reports, and maps. Borehole logs were used to determine the subsurface stratification, borehole casing, screen position, geological soil data and aquifer textural properties. Geological data was obtained from maps and reports from consultants and published hydrogeology and geology journals.

3.4.3 Evaluate aquifer types and groundwater flow regimes using derivative analysis

To achieve objective 2 of the study, time-drawdown, pumping and recovery aquifer test data was used to determine aquifer types and flow regimes encountered by groundwater as it flows from the aquifer to the well. This was done to identify the analytical model to use for aquifer parameter estimation from curve matching.

Various analytical models for interpreting pumping test under various conditions exist. Diagnostic plots were used for selection of an appropriate model to identify aquifer curve types and proper analysis methods. The three portions of the diagnostic plots were applied to identify wellbore storage, aquifer type model, and possible boundaries. Early data was used for identifying wellbore storage, intermediate data for identifying aquifer type model to be used and late data for identifying possible boundaries. The initial aquifer classification will be based on the geophysical logs and groundwater level monitoring. Final aquifer classification will be based on the results of the pumping test. Analysis of data collected during drilling and comparison of the plotted field data with the typical curves, aquifers pumped will be classified. Correct classification of the aquifer type is of vital importance as it will allow selection of the correct pumping test interpretation method that is for a test carried out in an aquifer test setup. It also facilitated the selection of the correct method for computation of groundwater flow using classical solutions. Type curves assume that the aquifer is of infinite areal extent and the overlying and underlying confining beds are impermeable with no recharge from other open water bodies and precipitation. Deviance from these assumptions results to departure from theoretical time vs drawdown plot.

3.4.3.1 Calculation of wellbore storage

$$s(t) = \frac{Q}{= \pi {r^2}_c} t$$

Q = pumping rate (m^3/s), t(s) = time, r_c (m) = radius of the well casing

apply a model that accounts for wellbore storage and skin effect i.e Papadopulos and Cooper (1967)

3.4.3.1 Data processing and analysis

Drawdown data was analysed using aquifer test pro version 5. The software allows automatic type curve fitting to pumping test. The software uses the downhill complex method which minimizes the algorithm for nonlinear functions and automatic curve fitting. This method requires much compute time, and an automatic fit was unreliable for observations under partial penetrating conditions. In instances whereby automatic curve fitting is feasible, data was manually fitted to the type curve using parameter controls based on the hydrogeologic and geologic conditions of the study site where data was acquired. The software uses theory of superposition for analytical solutions.

3.4.3.2 Calculation of log derivative

The derivative analysis method uses the logarithmic derivative of the drawdown, a method originally applied in petroleum engineering but now increasingly used by hydrogeologists. This method enabled a better interpretation and has been identified as useful in complex media such as fractured rock aquifers because it allows identification of aquifer characteristics such as well bore storage, recharge or barrier boundaries and flow conditions. The logarithmic derivative of drawdown was calculated from a series of drawdown and time data. The drawdown derivative was calculated using the following equation.
Below is the analytical equation representing drawdown in a borehole.

$$\mathrm{s} = 2.3 \frac{Q}{4\pi T t} \log \mathrm{C}$$

where *s* is the drawdown of the borehole, *Q* is the abstraction rate of the borehole, *T* is the transmissivity of the aquifer and *C* is a time dependant expression that differs based on aquifer type.

The derivative of drawdown with respect to log (*t*) is as follows.

$$\frac{\partial s}{\partial \log t} = 2.3 \frac{Q}{4\pi T}$$

The derivative of the logarithmic drawdown with respect to log *(t)* is as follows.

$$\frac{\partial \log s}{\partial \log t} = \frac{1}{\ln \mathrm{C}}$$

3.4.3.4 Flow regime identification and derivative smoothing

The variation in derivative curve values results to noisy data, thus making the interpretation difficult. In this study, the derivative curve has been corrected by smoothening based on the algorithm developed by Bourdet et al. (1989) where necessary as some curves required no smoothening. This method performs smoothening by considering and computing a series of instant *t* values separated logarithmically. This analysis facilitated the identification of flow regimes. The diagram established by Ehlig-Economides et al. (1984) in figure 3.5 which represents various flow regimes in a bilogarithmic scale, allowed identification of different flow regimes from the derivative curves. Diagnostic plots representing simultaneously the drawdown and derivative of the drawdown facilitated the choice of aquifer conceptual model as well as that of the appropriate analytical solution for the interpretation of each test. Geological information available through the 2D weathering profile thus makes it possible to validate these choices. To overcome the head losses issues induced by the pumping, we have prioritized the interpretation of drawdown data measured in the observation wells.

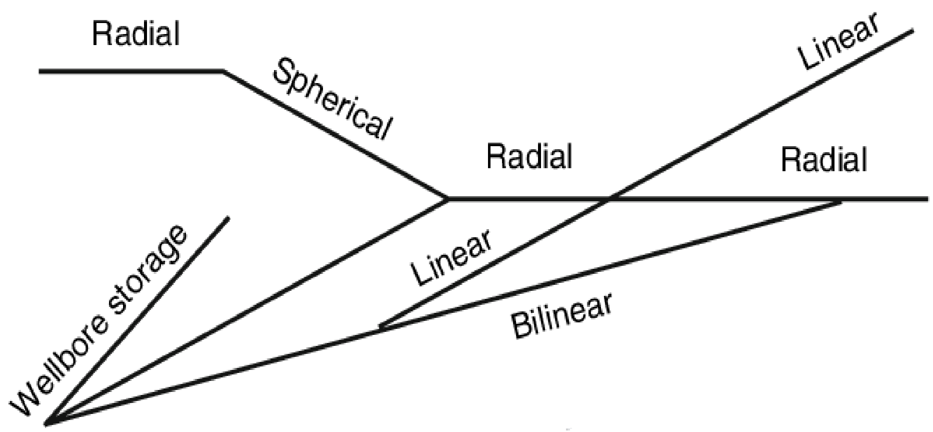


Figure 3.5: Flow regime identification tool

3.4.4 Estimate aquifer parameters

To achieve objective 3 of the study, each borehole drawdown data was analysed individually, and the method of analysis was derived from the diagnostic plots. A conceptual understanding of the geological setting was considered during data interpretation.

The imperative hydraulic parameters of interest which were determined through the analysis include hydraulic conductivity (K), specific yield (Sy), transmissivity (T) and storage coefficient, well yield, specific capacity, well efficiency and aquifer productivity. Aquifer hydraulic and transmissivity have been considered as parameters of interest because they explain properties of an aquifer controlling and allowing groundwater flow to well in different geological systems (Prince 2013). In this study, hydraulic conductivity, specific yield, transmissivity, storage coefficients were estimated. The specific capacity and aquifer productivity were acquired from secondary data of the study sites. These aquifer parameters were estimated using the pumping test method. The advantage with this method is that it provides in situ parameters over a large volume of an aquifer. The limitation with this method is that it is labour intensive and time consuming.

Aquifer parameters imperative in groundwater studies include storativity (S), transmissivity (T), specific yield (Sy), coefficient and specific yield were estimated to define the aquifer characteristics. Variables measured include the static water level, well diameter, distance between pumping and observation well, well location, depth and elevation, discharge rate and depth to water. A level logger was inserted into the borehole several minutes before pumping commenced to measure the static water level indicated by the sounder probe. The well diameter, location, depth, elevation, and distance to pumping well were all measured prior pumping of the boreholes. The discharge rate was measured during the pumping period for both hydraulic tests and will be used to estimate transmissivity and storativity of the boreholes. The depth to water level was measured at intervals during pumping and recovery test. This parameter was then used to calculate the drawdown for both hydraulic tests. Borehole yields were estimated using the ration of volume of water over time. The yields of boreholes were approximated from the ratio of volume of water over time, and the time it takes to make that volume.

Aquifer transmissivity was estimated using the Darcy's groundwater flow equation

$T = Kb$ where

T – Transmisivity (m^2/day)

K – Hydraulic conductivity (m/s)

b – Aquifer thickness (m)

Aquifer test pro was used to plot the drawdown vs time and recovery vs time graphs. Data was prepared prior input to the software. Data preparation involved calculation of drawdown from the static water levels for the different time intervals. Drawdown data will be plotted against time and the resulting curves will be compared to the typical curves. The drawdown was obtained by subtracting the water level at a given time from the water level before pumping commenced. The difference in the elevation of the water level before and after pumping will be plotted against time of pumping on a semi logarithmic graph sheet for the different locations. The graphs will be used to determine the drawdown per log cycle of time (ΔL) and the time intercept.

3.5 Limitations of the study

Data acquisition on the different study sites was quite a challenge because most of the newly drilled boreholes are situated in areas with limited hydrogeological information. Determining the site-specific hydrogeological information posed a limitation because readily available data is limited, however, unpublished reports from consultants were used to overcome this limitation, though the information was not quite enough. This study therefore does not provide full characterization of the aquifers but provided preliminary understanding of hydrogeological conditions on the borehole sites.

Chapter 4: Results and Discussion

Objective 1: Initial conceptualization of the groundwater flow system

4.1 Introduction

Hydrogeologists are concerned with understanding the geological aquifer properties and geological characterization served as the best means to achieve this objective. To provide an initial outline to understand groundwater flow system within the different study sites, initial cross sectional conceptual models have been developed for five hospital sites namely Caledon, Macassar, Gustrouw, Sonstraal and Paarl hospital. Subsurface geology, groundwater flow direction and static water levels was used to develop an initial conceptual model using information collected from geological reports, maps, and borehole logs for the selected study sites. The information was acquired through desktop study and previous work done on the study sites. This was done to address objective 1 of the study, which aimed at understanding the subsurface geological materials as they have a significant effect towards groundwater flow. Hydrogeological characteristics including groundwater sources, water table, aquifer parameters, flow regimes or boundaries have been used as additional information to produce an updated or refined conceptual groundwater flow model. Conceptual models fully characterizing the aquifer systems where boreholes of interest from the hospital sites have been drilled was then produced, presented in the last section of this chapter.

4.2 Interpretation and description of results

4.2.1 Initial Conceptual model

The TMG aquifer has a large areal extent, great thickness, and recharge. It is a regional fractured rock aquifer that has become a major source of bulk water supply to meet the agricultural and urban water requirements of the Western and Eastern Cape Provinces of South Africa. It is dominated by brittle, lithified and uniform sequence of quarzitic sandstone, siltstone and sandwiched shales with faults and fractures and a high potential of bulk water supply and a thickness ranging from 900 to 4000 m (Xu et al. 2009). The lithified sandstone and siltstones have zero primary hydraulic conductivity (Newton et al., 2006). Study sites of interest selected for conceptualization include Caledon, Gustrouw, Macassar, Sonstraal and Paarl hospital, drilled on the Malmesbury and TMG formation.

Boreholes penetrate either the Malmesbury or the TMG formation. The Caledon hospital site borehole taps on the TMG aquifer. This aquifer system is a heterogeneous and anisotropic body comprised of quartzitic sandstone with intergranular pore spaces intruded by quartz, making rocks to be nearly impermeable (Halbich and Cornell, 1983; De Beer, 2002). Fractures, faults, and folds within this aquifer have developed a fractured aquifer media thus producing secondary porosity, considered as a high yielding aquifer. Almost all major wellfields for water supply within the TMG have been developed within the vicinity of fault zones; hence the Caledon borehole was also drilled in a fault zone (Lin et al. 2007). The steeply dipping fault within the hospital site is formed by the contact between Gydo and Peninsula formation. It was assumed to be the major water bearing structure because faults within this aquifer have been acknowledged to play a key role in groundwater occurrence in the sandstones. However, this was not the case at the Caledon hospital site because the fault with multiple fractures from the Peninsula formation were not water bearing. Geological materials with the Caledon study site include unconsolidated loamy clay forming an overburden, underlain by the unconsolidated silty clay of the Gydo formation, also underlain by white consolidated medium grained quartzitic sandstones of the Peninsula formation. Impermeable shale is the dominant geological material within the site.

Though the TMG aquifer has been considered as the most favourable target zone for groundwater exploration, however, Conrad et al., (2019) stated that the Malmesbury aquifer is also a high yielding aquifer with favourable groundwater quality; hence it was also utilized as a target zone for groundwater augmentation in hospitals and community health centres. The geological materials of the Malmesbury Group are formed by the western branch of the Saldanha belt comprised mainly of meta-sedimentary and meta-volcanic rocks. It is dominantly composed of highly lineated and foliated greywacke, schist, phyllite, shale, conglomerate and limestone (Belcher, 2003). It is subdivided into three different terrains separated by parallel faults considered to be due to accretionary tectonics. The three terranes include the Boland, Swartland and Tygerberg. Formations within the Boland terrane include Brandwacht, Porteville, Noree and Piketburg. Formations within the Swartland terrane include the Franschhoek, Bridgetown, Moorresburg, Klipplaat, and Berge River. The Tygerberg terrain is formed by the Tygerberg formation. Brandwachct formation is comprised of grewacke and pelites and the Porteville formation is composed of fine to medium quartzitic sandstone. The Noree formation is composed of phyllite, medium grained limestone, dolomite, feldspathic and sericitic quartzite. The Piketberg formation is comprised of strongly foliated and lineated greywackes, conglomerate, feldspathic quartzites, feldspathic grits and minor marly limestones. The Franschhoek formation of the Swartland terrane is comprised of feldspathic and sericitic arenites with feldspathic conglomerates and intermittent shale beds. The Bridgetown formation is comprised of dolomite, minor graphitic schists and shales and the Moorreesburg formation consists of a series of greywacke and well laminated quartz muscocvite biotite schist. The Klipplaat formation is comprised of grey to yellowish quartz whilst the un-metamorphosed Berg River formation is composed of Mica schists and greywackes with limestone layers. The Tygerberg formation is comprised of finely pelitic rocks containing greywackes and immature quartzites. The aquifer is high yielding with a moderate groundwater quality. Structurally, the Malmesbury group is characterized by upright open to tight folding and axial planar cleavage. The yield is usually <0.5 l/s.

Paarl and Sontraal site conceptual cross section is represented in figure 4.1 below. Based on the 1:1000 000 geological map of South Africa from the Council of Geoscience; Paarl borehole taps on a fractured rock aquifer (Musekiwa et al., 2011). The site is overlain by a thin layer of highly weathered unconsolidated fine to medium sand with clay and silt particles which can be categorized as alluvial deposits of the Enon formation. Water is trapped in pore spaces of unconsolidated alluvium deposits forming the primary aquifer. This formation is underlain by a thick layer of unconsolidated silt and clay mostly dominated by the clayey material. The underlying bedrock is comprised of grey-black consolidated shale of the Malmesbury formation that has been metamorphosed into hornfels. Groundwater is trapped in joints, fissures, and fractures at a depth of approximately 36m of the Malmesbury formation forming the secondary aquifer (Engelsman et al., 2000).

Grabouw borehole taps on the Rietvlei formation of the TMG, a fractured hard rock aquifer. The uppermost layer is the thinly poorly sorted fine to medium unconsolidated sand from eroded material of quartzite deposits forms upper most units. Underlying this is approximately 14m thick unconsolidated sandy loam comprised of fine sand with clay and silt underlain by quartzitic sandstone. The matrix is composed of fine to medium sand grains.

Sontraal borehole taps on the Malmesbury formation as represented in figure 4.1 below. The top layer of the study site is comprised of thick unconsolidated silty clay. Underlying this layer is the hard rock Malmesbury shale acting as transmissive zones facilitating groundwater flow. The aquifer is alluvial with fine unconsolidated particles of silt and clay and larger particles of sand and gravel. A perennial river runs through the site. Further investigation of geological materials between the two sites is recommended since the cross sections were developed with limited geological information.

Grabouw hospital site is comprised of 3 layers. The top layer is 5m thick and consists of thin poorly sorted fine to medium unconsolidated sand. The top layer is assumed to be eroded materials from the surrounding quartzite deposits. Underlying this is the 14m thick unconsoidated sandy loam composed of fine sand with interstitial clay and silt. Underlying this is a hard consolidated quartzitic sandstone. Based on information acquired from the geological map, this layer is likely to be the Rietvlei formation of the Table Mountain Group.

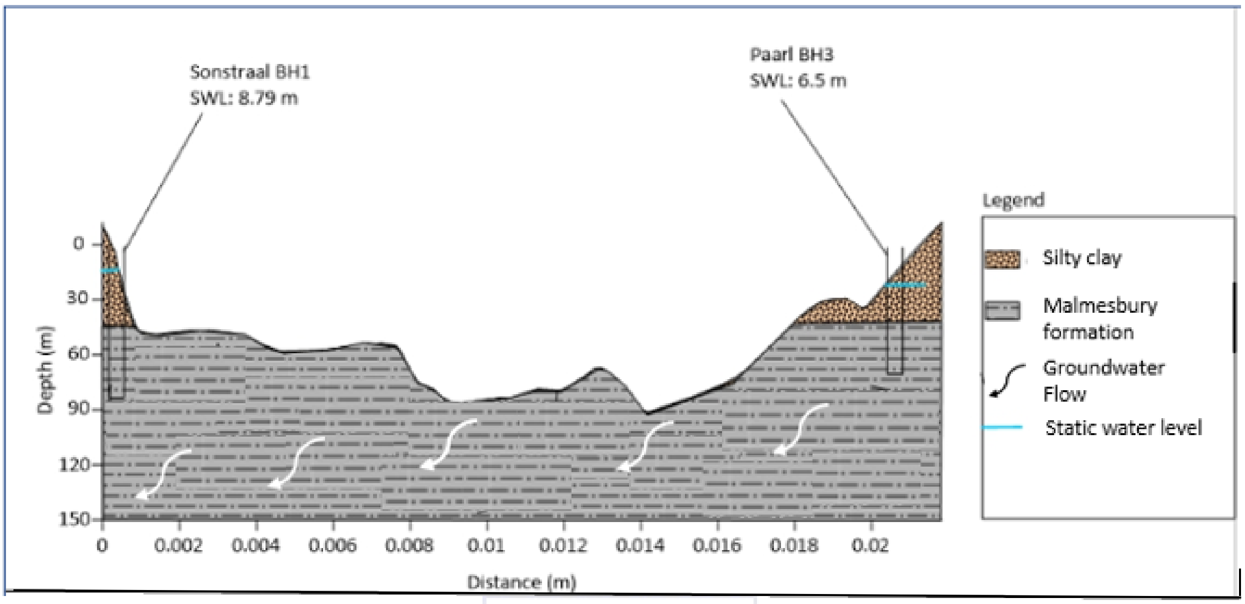


Figure 4.1: Conceptual cross section presenting hydrogeological conditions of Paarl and Sonstraal study sites

The conceptual cross section of Macassar and Gustrouw site is presented in figure 4.2 below. In reference to the 1:1000 000 geological map of South Africa from the Council of Geoscience, Macassar borehole taps on fractured and weathered rock aquifer (Musekiwa et al., 2011). The upper most layer of the Macassar site is formed by the Springfontein formation with eroded material and unconsolidated fine to medium white sand, clay and calcareous material with commuted shells, pebbles, and shells locally along the beach. Underlying this formation is mostly clay and interstitial sand which could have been formed by weathering of the underlying bedrock of the Malmesbury group shale whilst the bedrock is comprised of the Malmesbury group rocks with hard shale deposits. The aquifer borehole is drilled along the coast in an aquifer characterized by shallow water table conditions and highly conductive gravel-sand hydrogeologic units. Such hydrogeological characteristics are good for groundwater yield and abstractions Gomo et al., (2013), Musekiwa et al., (2011). Groundwater flow is from inland, across the Project site, in a south-westerly direction towards the coast, where it discharges into the ocean.

The figure 4.2 below shows the conceptual cross section of Gustrouw hospital site. The borehole taps on the weathered Malmesbury aquifer overlain by quaternary sediments which include loam and sandy loam deposits. The overlying sandy loam deposits are comprised predominantly of clay and underlying this is the poorly consolidated weathered Malmebury group rocks. Geological structures in proximity to the site include an anticline and fault closer to ocean. The prevailing geology of the Gutrouw study site suggests that the aquifer is shallow, unconfined, and highly weathered Malmesbury. Furthermore, this suggests that the aquifer will be easily depleted because some of the water might be lost to evaporation. Further investigation of the geological materials between the two sites is recommended since the cross sections were developed with limited geological information.

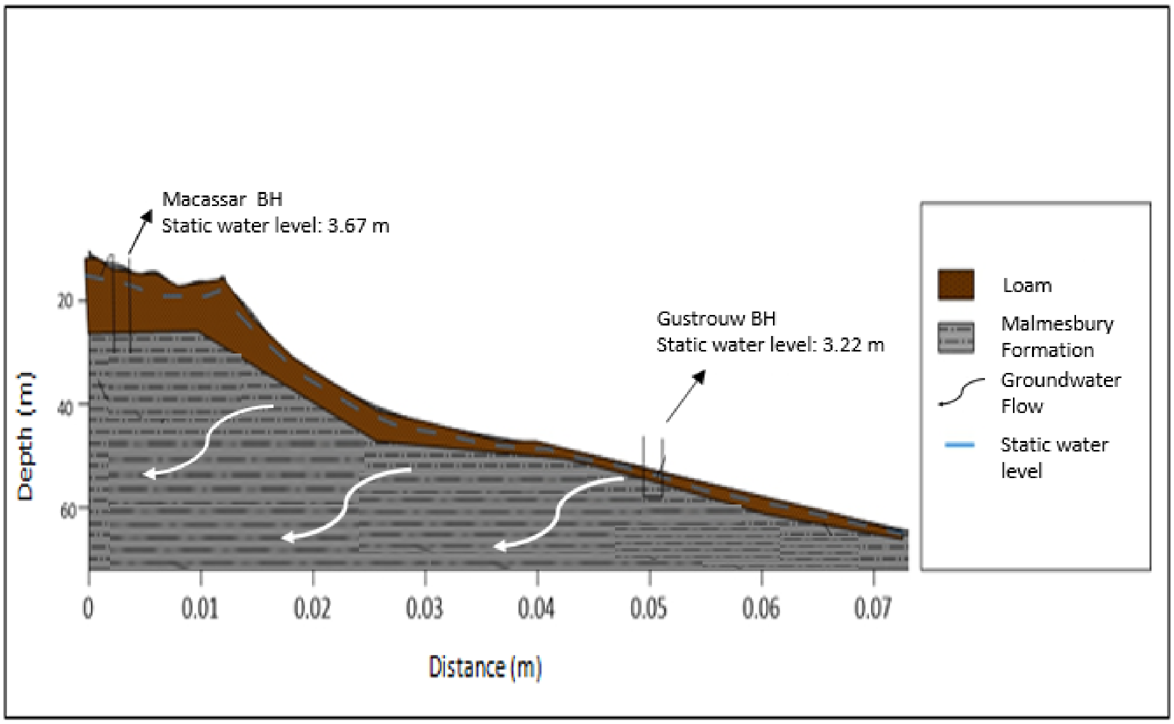


Figure 4.2: Conceptual cross section presenting hydrogeological conditions of the Macassar and Gustrouw study site

4.2.2 Borehole logs

Geological information and borehole data from drillers provided insights on hydrostratigraphic units for each of the study areas. Figure 4.3 shows borehole log of Macassar study site. The uppermost unit of the Macassar site, with a thickness of 6m consists of unconsolidated fine to medium sand with clay and calcareous material. This layer is deposits of the Springfontyn formation with eroded materials from the underlying mud deposits. Underlying this formation is the 6m thick clay with interstitial sand which could be a result oof weathering of the underlying bedrock. Underlying this formation is a 36m bedrock comprised of shale of the Malmesbury Group. The static water level occurs at 3.03m. Water strike occured occured at 30m in the Malmesbury formatio

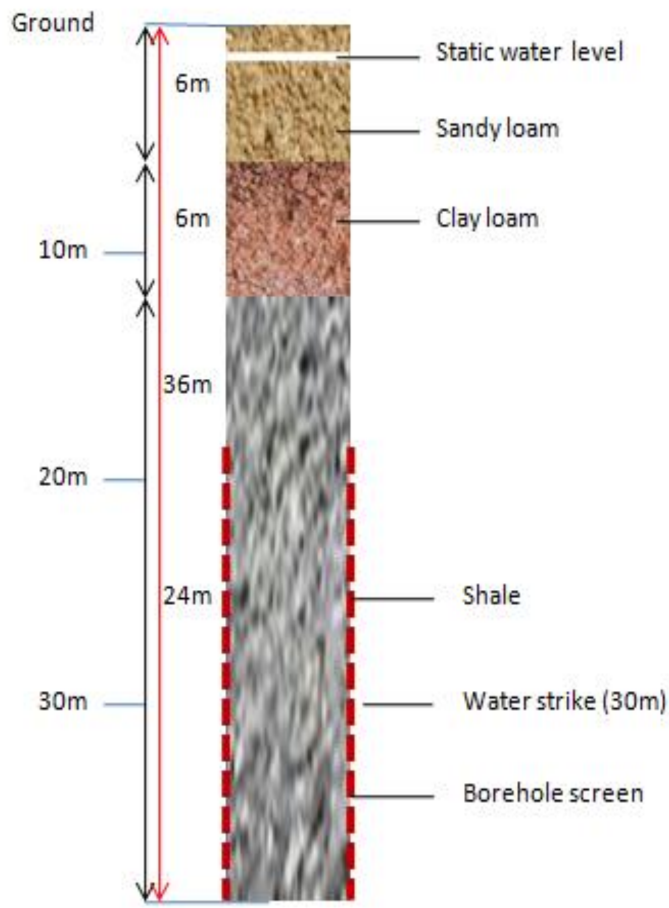


Figure 4.3: Macassar hospital borehole log

Figure 4.4 shows the borehole log of Gustrouw study site. The 6 m thick overburden of the site is comprised of loam deposits. The loam deposits are eroded products of the nearby granitic material. Underlying this is the 42m thick poorly consolidated Malmesbury shale from the Tygerberg group. A water strike was intercepted at 38m in the Malmesbury group.

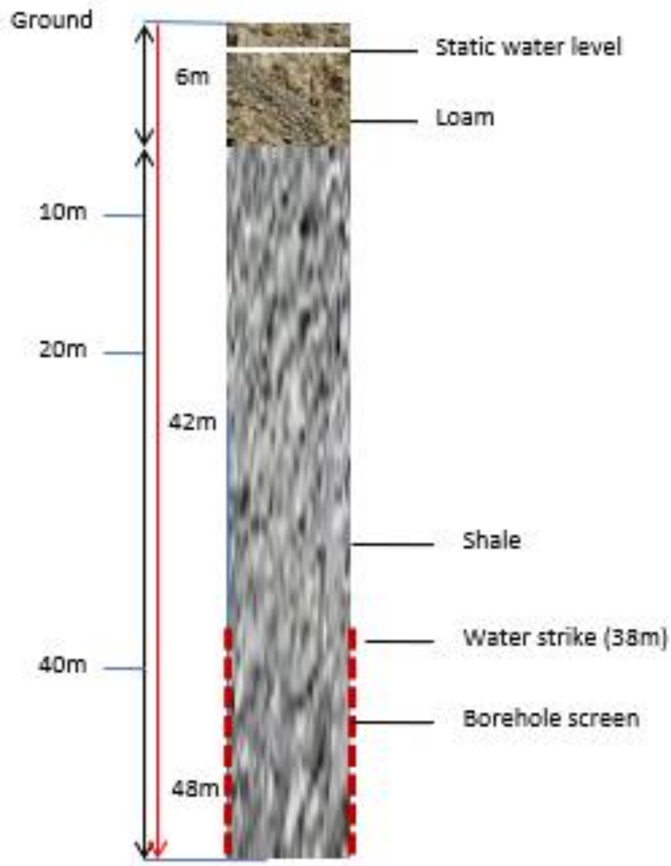


Figure 4.4: Gustrouw hospital borehole log

Figure 4.5 below shows the borehole log of Paarl study site. It is comprised of 3 layers with varying thickness as presented in top layer is 5m thick fine to medium sand underlain by a 32m thick layer of unconsolidated silt and clay. The basement layer is of the Malmesbury Group intruded by the Cape Granite suite at a depth of about 30m. The static water level lies at 6.5m depth. The water strikes were observed at 32m, 59m, and 44m depth.

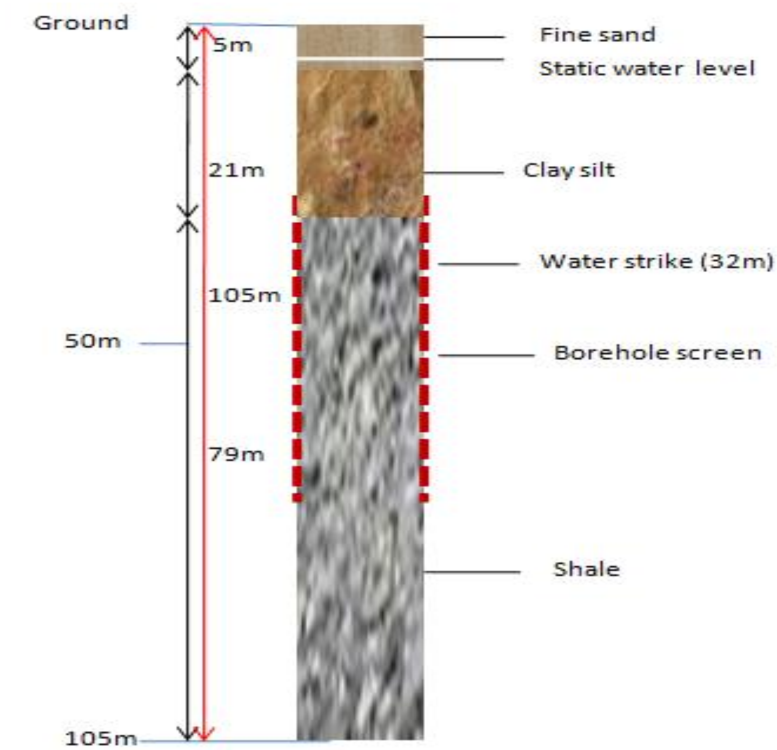


Figure 4.5: Paarl hospital borehole log

Another borehole site studied is located at Grabouw hospital and the log is presented in figure 4.6 below. The site is comprised of 3 layers. The top layer is 5m thick and consists of thin poorly sorted fine to medium unconsolidated sand. The top layer is assumed to be eroded materials from the surrounding quartzite deposits. Underlying this is the 14m thick unconsoidated sandy loam composed of fine sand with interstitial clay and silt. Underlying this is a hard consolidated quartzitic sandstone. Based on information acquired from the geological map, this layer is likely to be the Rietvlei formation of the Table Mountain Group. The static water level is at 11.25m. Water strikes occurred at 30m and 43m with the Rietvlei formation which is a fractured rock aquifer. The Table Mountain Group is considered a high yielding due to the presence of high yielding water bearing fractures. This was also proved by the water strike at 43m which provided a greater yield of approximately 5l/s.

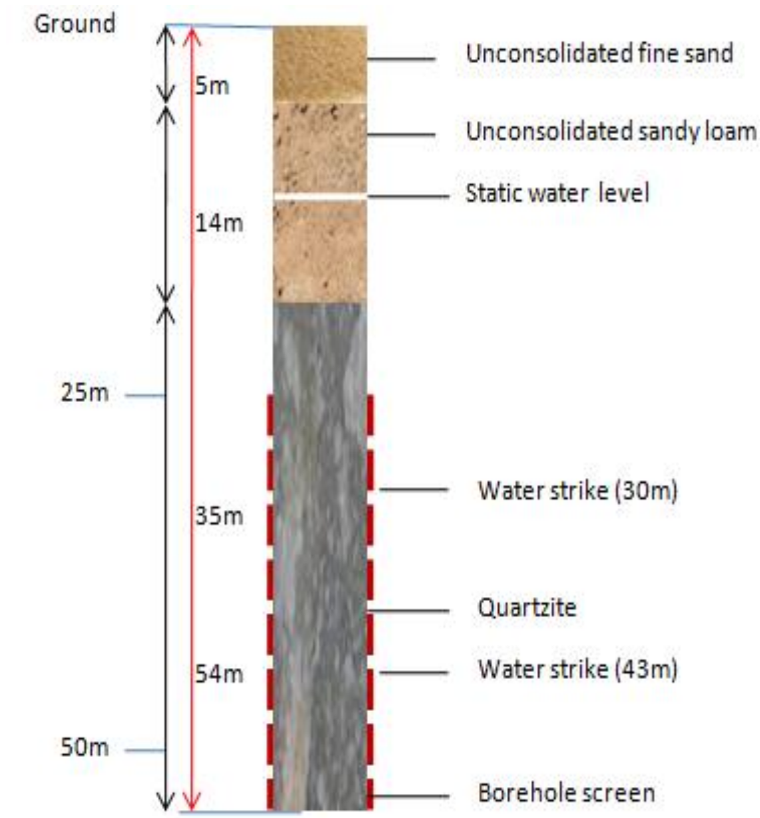


Figure 4.6: Grabouw hospital borehole log

Figure 4.7 below presents the borehole log of Sonstraal study site. The overburden of the borehole site is the unconsolidated silty clay with a thickness of 63m underlain by 23m thick consolidated shale of the Malmesbury Formation. This material is assumed to be weathered granite from the nearby Paarl granite pluton. Water strikes were intercepted in the upper section of the Malmesbury group at a depth of 54 and 70m. The static water level was observed at 8.79 m depth.

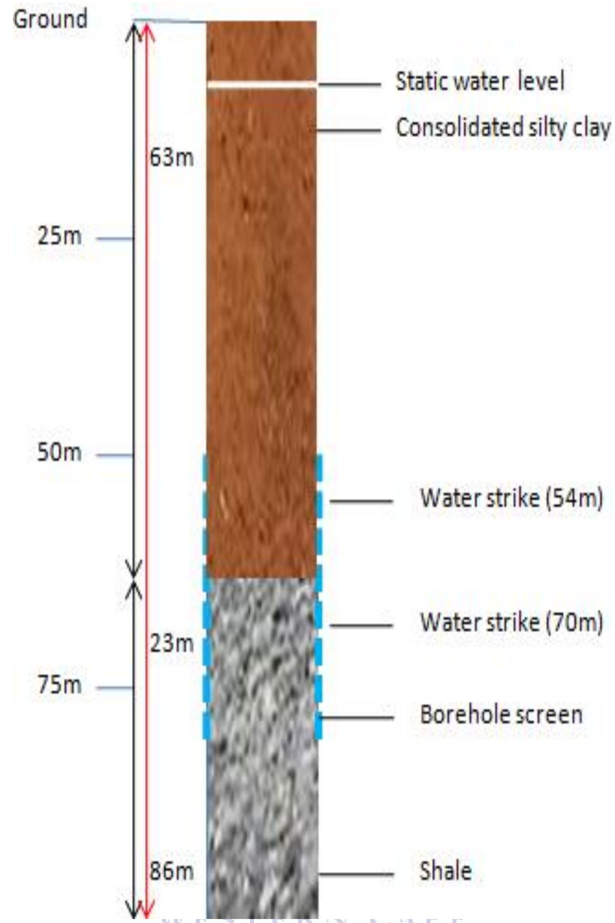


Figure 4.7: Sonstraal hospital borehole log

Figure 4.8 below shows the borehole of Macassar study site. The surface layer of Caledon study site is a thick whitish to pinkish unconsolidated loamy clay which mostly results from weathered sandstone and mudstone. This layer is 24m thick. Underlying the surface layer is a 106m thick white consolidated medium grained quartzitic sandstone of the Peninsula formation. The static water level lies at 10.52m and the water strike occusrs at 41m, 103m and 114m. The borehole has been drilled to a depth of 165m. Borehole 2 of the Caledon study site is comprised of a 40m thick subsurface of unconsolidated loamy clay and a 125m thick quartzitic sandstone of the Peninsula formation. The static water level lies at 10.55m.

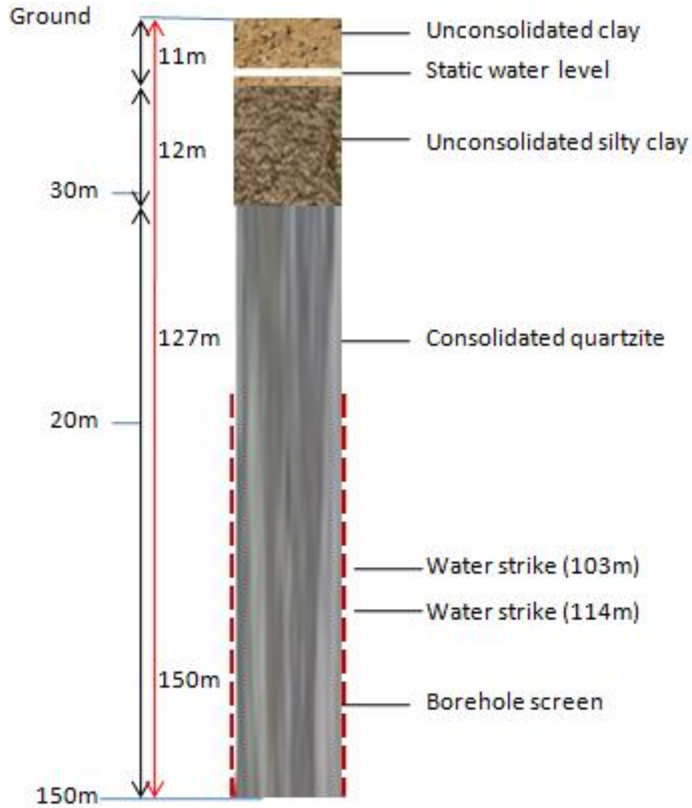


Figure 4.8: Caledon hospital borehole log

4.3 Interpretation of results

The fractured rock aquifer of the Malmesbury Group shale is likely to receive recharge via the Berg River and associated saturated alluvium, as well as intersecting higher yielding fractures at depth (DWAF 2008). Groundwater recharge is assumed to occur directly through precipitation in areas immediately surrounding faults. This may be a concern for long sustainability of the aquifer system if the fracture networks are depleted faster than the recharge to these systems (Conrad et al., 2019).

Prevailing geology of the Paarl borehole suggests that the site has two aquifer types. The aquifer appears to be confined as the main water strike is at the contact zone between shale and clay. Overlying unconsolidated sand traps water into pore thus forming a primary aquifer because sandy materials allow surface water to infiltrate. The unconsolidated silty and clay layer in the subsurface forms a perched water table as the surface water accumulates above the clay layer due to low infiltration capacity. This prevents penetration of the infiltrated water to the secondary aquifer, resulting to water flow towards the Berg River. Groundwater flow occurs in a south easterly direction toward the Breede River. Results from a study by Conrad et al., (2019) demonstrated that the Malmesbury aquifer is a favourable aquifer in certain areas with high aquifer yields and favourable water quality.

Geological features of the Grabouw and Caledon study sites suggested that boreholes from the 2 sites tap on the Peninsula formation of the Table Mountain Group aquifer. The Peninsula formation has a low primary porosity due to cementation of sand grains. The Peninsula aquifer is highly fractured with lower shale content than the Nardouw aquifer. The aquifer system is highly heterogeneous due to the large variation in hydraulic properties of water bearing fractures and rock matrix. The aquifer heterogeneity is believed to have been exacerbated by the folding of rocks of the Cape Supergroup, thus adding heterogeneity and anisotropy of the aquifer system. The aquifer is highly fractured, and fractures act as permeable conduits for rapid groundwater flow while matrix blocks form main storage and unit reservoir. TMG rocks are therefore considered to form double porosity and fractured rock aquifer systems with variable transmissivity and storativity hence the porosity of this aquifer is categorised as secondary (Duah 2010).

Groundwater flow within the aquifer occurs through fractures and faults. The predominant direction of fault is northwest to southeast. Groundwater flow in the high yielding zones occurs through fault related damage zones with a magnitude greater than what is normally abstract-able from areas with minor fracturing and faulting of geological materials.

Some boreholes drilled into Malmesbury Group shales are likely to receive recharge via the Berg River and associated saturated alluvium, as well as intersecting higher yielding fractures at depth (DWAF 2008). Groundwater recharge also occurs directly precipitation in areas immediately surrounding faults. This may be a concern for long sustainability of the aquifer system if the fracture networks are depleted faster than the recharge to these systems (Conrad et al., 2019).

Groundwater flow within the Malmesbury aquifer in the high yielding zones occurs through fault related damage zones with a magnitude greater than what is normally abstract-able from areas with minor fracturing and faulting of geological materials.

4.4 Evaluation of study based on results

This chapter presented results of the initial conceptual model of the study sites where boreholes for groundwater augmentation have been drilled. The main aim of this objective was to understand the subsurface geological materials because they have a significant effect towards groundwater storage and flow to boreholes. The argument in this chapter is that if the subsurface geology is understood prior analysis of the pumping test data, then the results portrayed from the analysis will be interpreted based on the geological information to be able to detect errors and acquire reliable results from the pumping test data. From the findings, it was concluded that the TMG aquifer has a bulk water supply due to its fractured nature whilst the Malmesbury formation has a limited water supply because it is comprised of the less permeable shale layers thus resulting to delayed groundwater recharge. It is therefore recommended that the TMG aquifer should be targeted for bulk groundwater supply. On the other hand, geological results revealed even though the Malmesbury is known as a low yielding aquifer, there are zones with bulk water supply such as the Paarl site and should be targeted for reliable groundwater supply. The results acquired are considered as reliable because they agree with the results reviewed from previous studies. This is evident from the borehole logs and the initial conceptual models created.

4.5 Implication of results for practice and policy

The findings have unveiled the geology of the subsurface in each of the study sites. Furthermore, the depth of boreholes has been presented clearly to illustrate the geological formations in which each of the boreholes has been drilled. This was done to address objective 1 of the study, which aimed at understanding the subsurface geological materials as they have a significant effect towards groundwater flow. The findings from this study will help in ensuring that further exploration from the TMG and Malmesbury aquifer is done on sites with a bulk water supply and geological materials that are transmissible enough to produce reliable and long-term borehole yields. This will therefore contribute towards informed decision making with regards to water resource management within the province.

Objective 2: Evaluate aquifer types and groundwater flow regimes using derivative analysis

4.1 Introduction

Derivative analysis has been widely used to understand how groundwater flow to wells is affected by complexity and heterogeneity of aquifer systems. This section of the study presents and discusses results on derivative analysis of pumping test from the TMG and Malmesbury aquifer, where hospital boreholes have been drilled thus addressing objective 2 of the study. The aim of this objective was to identify aquifer types, flow regimes, boundary conditions and aquifer heterogeneity influencing groundwater flow to wells to identify an appropriate groundwater flow conceptual model and for interpretation of pumping test data. Furthermore, it addresses the knowledge gap on complex aquifer heterogeneity influencing groundwater flow to wells within the selected borehole sites. This was imperative to ensure that pumping test data analysis is performed using the appropriate analytical models relevant for the hydrogeological conditions of the aquifer. To achieve this objective, secondary pumping test data from the Western Cape government was used to produce derivative plots for interpretation and discussion.

4.2. Interpretation and description of key results on derivative analysis

The drawdown log-log and semi log plot of the Macassar borehole portray 4 distinct groundwater flow characteristics: deviation of derivative from the drawdown plot, transition period, non-radial acting flow, and a single impermeable boundary. The derivative plot portrays no wellbore storage effect, thus indicating that there is no stagnant water in the borehole, water is withdrawn directly from the aquifer. The dipping down of the derivative indicates rapid release of water from the sand gravel aquifer materials. Multiple oscillations occur during mid-time thus indicating non-radial flow conditions. Furthermore, this suggests that groundwater flows through geological materials with variable transmissivity, thus indicating aquifer heterogeneity. The single impermeable boundary only reduces the overall aquifer supply into the boreholes because the other sides of the aquifer are still able to contribute to the flow towards the pumping borehole. Fracture dewatering occurs as drawdown continues to increase thus indicating a decrease in trasmissivity (Holland 2011). Downward plunging of the derivative curve from the 1000th minute indicates that a constant head boundary is encountered. Such an aquifer can be regarded as a more productive aquifer. Furthermore, this is confirmed by the conceptual model which described the aquifer as coastal, thus indicating that the borehole is high yielding and may regraded as a primary target for water supply. Based on the results from the initial conceptual model, the borehole is in a coastal area with an aquifer characterized by shallow water table conditions and highly conductive gravel-sand hydrogeologic units. Such hydrogeological characteristics are good for groundwater yield and abstractions Gomo et al., (2013), Musekiwa et al., (2011). Based on the derivative plot and theoretical classification of derivative plots by Renard et al., (2009), this borehole has been drilled in a double porosity aquifer. This is presented in figure 4.9 below.

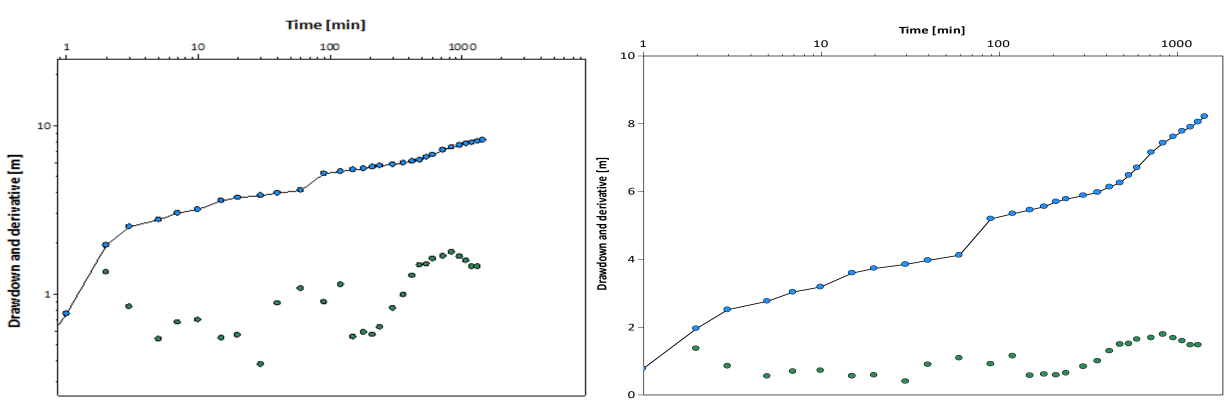


Figure 4.9: log-log and semi-log derivative plot of Macassar hospital borehole

The log-log and semi-log plots of the Paarl site shown in figure 4.10 portray three distinct groundwater flow regimes, wellbore storage effect during early time, infinite acting radial flow and recharge or constant head boundary. The plot represents an infinite confined aquifer that is approximately homogenous. The derivative curve follows the drawdown curve during early, thus suggesting that water is withdrawn from the borehole itself. From the 10th minute, pumping pressure spreads rapidly thus resulting to a quick drawdown response as the aquifer experiences full stress from pumping. Dip in drawdown derivative after departing from the drawdown curve is due to the rapid release of water from groundwater trapped in joints, fissures, and fractures at a depth of approximately 36m of the Malmesbury formation forming the secondary aquifer as stated in the previous objective (Engelsman et al 2000, Van Tonder 2001, Gomo 2011). During mid-time, water from the aquitard is leaking into the aquifer. Eventually at late time, all leakage through the aquitard becomes constant and flow towards the well reaches a steady state. This behaviour is also observed when the cone of depression reaches a recharge boundary. Renard et al., (2009) highlighted that a leaky aquifer case can be distinguished from a constant head case by looking at the shape of the derivative. The derivative tends towards zero earlier in the case of leaky aquifers and much faster than in the case of a constant head boundary. In reference to the theory on derivative plots by Renard et al. (2009), the derivative plot suggests a leaky confined aquifer. This suggests that towards late time, the water is pumped from the aquitard.

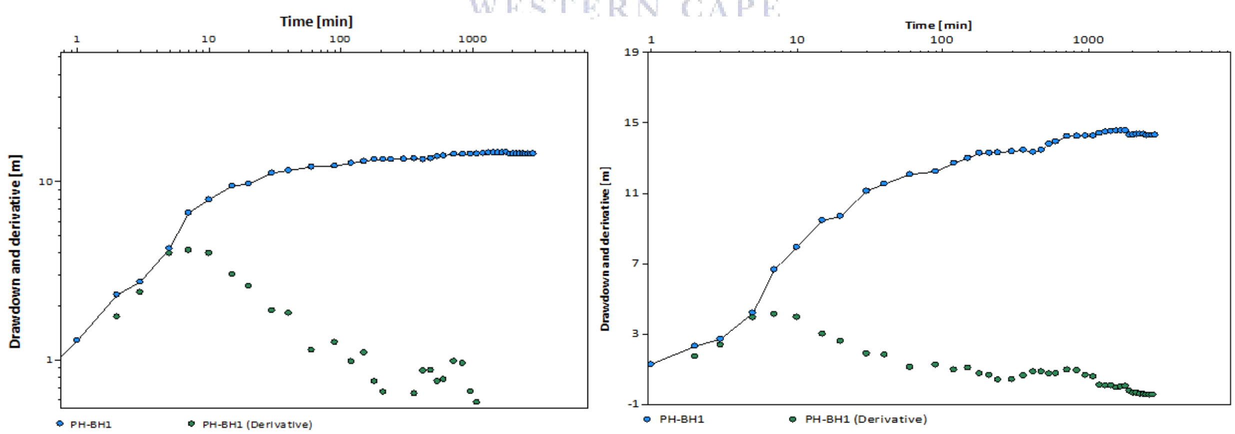


Figure 4.10: log-log and semi-log derivative plot of Paarl hospital borehole

The diagnostic plot of the Grabouw hospital site represents an infinite confined aquifer that is approximately homogenous as shown in figure 4.11 below (Roslan, 2017). The peak in the derivative curve towards late time indicates an impermeable boundary condition (Ferroud et al., 2018, Gomo

2011). Late time portion of the plot also portrays the presence of a fault on the aquifer. The log-log plot portrays a radial flow condition from the 10th to 150th minute. The semi log plot portrays a derivative plateau from the 10th to the 100th minute, thus suggesting radial flow conditions during mid-time. This is expected in fractured confined aquifers with aquitard above and below by impervious materials. The radial flow conditions indicate that during mid-time, water flows through homogenous geological materials with uniform transmissivity. The drawdown plots as straight horizontal line thus also suggesting radial flow condition in the aquifer. The drawdown derivative deviates and steepens upwards towards late time, thus suggesting that the cone of depression reaches an impermeable boundary. The cone of depression reaching a barrier boundary results to doubling of the drawdown. Results obtained are like those from a case study in confined sandstone aquifer of the Convey Hill formation of Mirabel. Drawdown derivative plot from the study portrayed two successive radial and non-radial flow conditions (Ferroud et al., 2018).

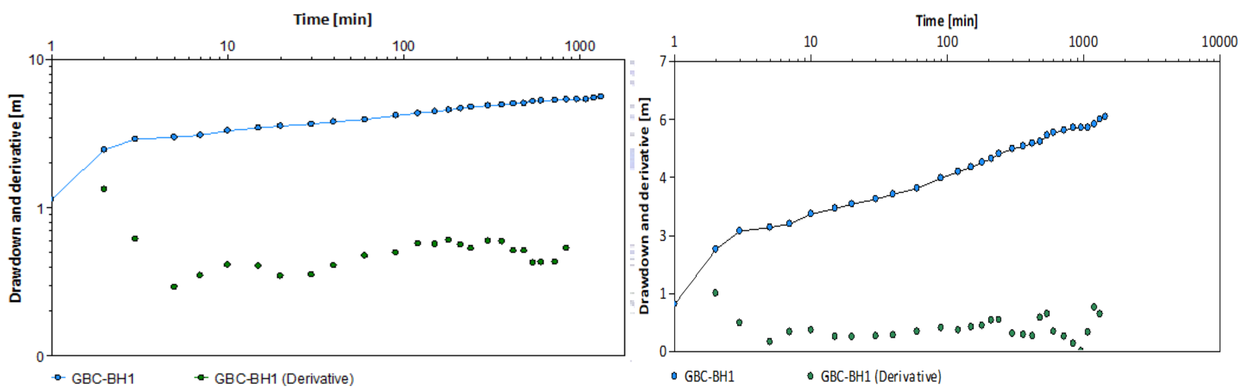


Figure 4.11: log-log and semi-log derivative plot of Grabouw hospital borehole

The Sonstraal hospital site aquifer as displayed in figure 4.12 below has linear flow regime and this is portrayed by drawdown increase whilst the derivative curve reaches a plateau during mid-time. This may be interpreted as a linear flow regime (Ferroud et al., 2018). The derivative plot shows 3 distinct flow regimes which include linear flow, infinite acting radial flow, recharge boundary or constant head boundary. The linear flow occurring during early time may be indicative of fracture flow. The infinite acting radial flow occurs during mid-time, characterized the derivative curve forming a plateau. The start of radial flow indicates the time at which the fractured reservoir starts to behave as homogenous (Ferroud et al,. 2018). Towards late time, the derivative plot plunges towards 0 thus suggesting the occurrence of a recharge boundary. In reference to the theoretical curves by Renard et al., (2009), this behaviour is like a leaky confined aquifer with a compressible aquitard and constant head boundary.

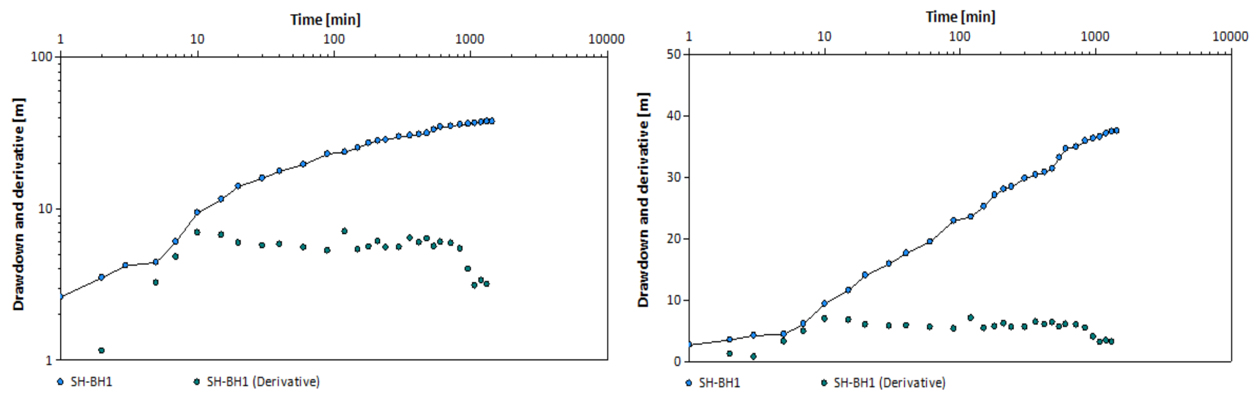


Figure 4.12: log-log and semi-log derivative plot of Sonstraal hospital borehole

The Caledon hospital site diagnostic plots in figure 4.13 show that flow comes from storage in fractures. A transition occurs during mid-time as the matrix blocks feed the water at a fast rate to the fractures, thus resulting to a stabilised drawdown. During late time, the pumped water comes from storage in both fractures and matrix blocks. The plot therefore portrays double porosity aquifer behaviour. The derivative plateau with a slope of 0 during middle to late period indicates that fractures are well connected far from the borehole. During this period, groundwater is withdrawn from the matrix blocks thus resulting to stabilization of drawdown and derivative, suggesting radial flow conditions. The drawdown curve deviates downward towards 1000th minute and upwards after the 1000th minute. pump stopped working after 1000 min and recovered a little bit, hence the drawdown curve deviates upwards.

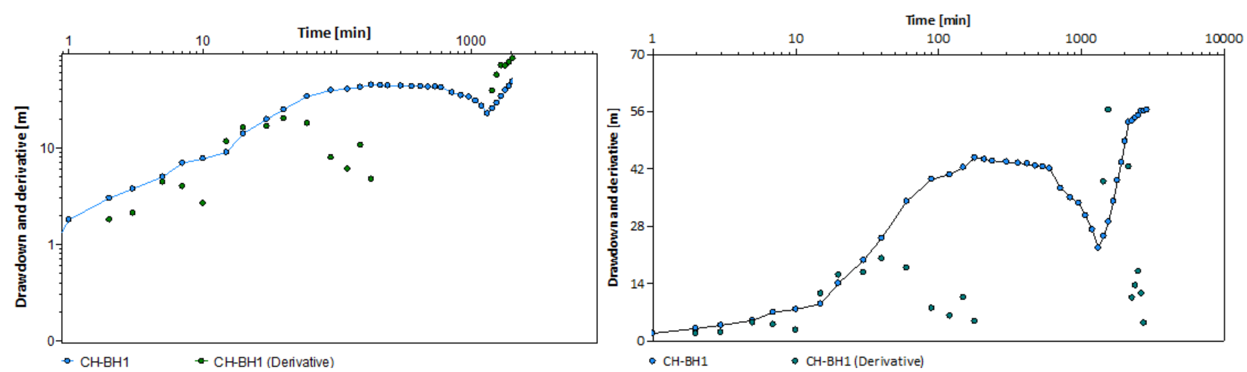


Figure 4.13: log-log and semi-log derivative plot of Caledon hospital borehole

4.4 Comparative analysis of results

Section 4.2 above presented results on derivative analysis for different boreholes drilled in the Western Cape for the drought relief business continuity program. Due to the difficulty in identifying an appropriate theoretical model that fits the observed pumping test data, derivative analysis was used to identify the typical drawdown behaviour in the study areas. The observed data sets were compared to a set of typical diagnostic plots to identify aquifer flow regimes and the model that can be used to interpret data.

A study by Holland (2011) focused on hydrogeological characterization of crystalline basement aquifers. The aquifers were characterized by performing a pumping test. Holland (2011) used derivative analysis for pumping test interpretation with the aim of identifying an appropriate model that fits the observed pumping test data. Comparable to the results obtained from Macassar and Gustrouw hospitals sites of the current study, a double porosity aquifer response was detected in 3 boreholes from the study site. The depth of boreholes ranges between 40 and 50, like the depth of boreholes from the above-mentioned sites. This explains shallow drilling depths with a potential high risk of borehole failure during droughts. Equivalent to the current study, the Moench analytical solution was identified as the most appropriate model to analyse the pumping test data based on the derivative analysis results, thus proving that the analytical model selected is appropriate.

A study focusing on drawdown log derivative analysis for interpreting constant rate pumping test was conducted in an inclined substratum aquifer at Mirabel Phillipon by Ferroud et al., (2019). Hydrogeological information revealed that the aquifer has a confining layer of clay with fractured sandstone underlying the confining layer. The diagnostic plot results agree with the hydrogeological information because it categorised the aquifer as leaky and confined. When the results by Ferroud et al. (2019) are compared with those obtained from Sonstraal study site, a similarity is observed thus proving that the method applied on the current study was successful.

Odiyo et al., (2017) studied groundwater yield reliability analysis and operating rules for data constrained rural areas in South Africa. The hydrogeological information revealed that the study was conducted in a fractured rock aquifer comprised of sandstone, quartzite, and basalt like the hydrogeological conditions of the current study site. Results on diagnostic plots portray a double porosity aquifer characterised by fracture dewatering or different dips during late time. The results from Macassar study site of the current study also portrayed double porosity behaviour, however, the geology and conceptual models for these sites are different. This suggests that the analytical model selected for pumping test data analysis is appropriate. Furthermore, the flow regimes identified from the plots are representative of the aquifer hydrogeological conditions.

4.5 Evaluation of study based on results

This chapter presented results on derivative analysis of pumping test data thus addressing objective2 of the study which is to determine aquifer types, flow regimes and boundary conditions using drawdown derivative analysis. The main aim was to understand the aquifer hydrogeological conditions to identify appropriate analytical model for pumping test data analysis. The argument in this chapter is that if the hydrogeological conditions of the aquifer are understood prior selecting the analytical model of analysis, then reliable estimates of aquifer parameters to understand aquifer productivity will be obtained.

Results obtained suggested that boreholes were drilled in the fractured bedrock and unconfined aquifer of the Table Mountain and Malmesbury Group. The derivative plots and drawdown behaviour portrayed double porosity, leaky confined and confined aquifer behaviour. The double porosity and leaky confined aquifer behaviour were identified from Maccassar, Paarl and Sonstraal sites, respectively.

Confined aquifer behaviour was identified at the Grabouw study site. Double porosity aquifer behaviour was portrayed by the stabilization of drawdown during mid-time of pumping, suggesting that the matrix blocks feeds fracture with water at an increasing rate or the vertical delayed recharge from the overlying permeable part in an unconfined aquifer. The leaky confined aquifer behaviour was identified by looking at the shape of the derivative in which the derivative tends towards zero earlier in the case of leaky aquifers and much faster. The confined aquifer at the Grabouw site behaviour was portrayed by the impermeable boundary condition represented by the peak in the derivative curve towards late time. Furthermore, the semi log plot portrays a derivative plateau from the 10^{th} to the 100^{th} minute, thus suggesting radial flow conditions during mid-time and such behaviour is expected in confined aquifers bounded above and below by impervious materials. These findings are supported by Renard et al. (2009), Holland et al., (2011) and Roslan (2017).

4.6 Implication of results for practice and policy

The findings have unveiled the formation heterogeneity, boundaries, and flow regimes of aquifers on study sites thus demonstrating that derivative analysis is an easy and powerful tool to assess. This therefore enhanced the understanding of how these factors influence groundwater flow to wells. This method also provided useful information for conceptualising aquifer characteristics, moreover, facilitating the selection of an appropriate analytical model to evaluate and understand the hydraulic parameters of the aquifers. It is therefore recommended that derivative analysis should be considered as a mandatory tool for pumping test analysis among hydrogeologists to ensure that reliable results for conceptual model building are acquired.

Objective 3: Estimation of aquifer parameters

4.1 Introduction

Estimation of aquifer hydraulic parameters is important for prediction of future availability of groundwater. This section presents and discusses aquifer parameter estimation results from different hospital facilities where groundwater supply was augmented thus addressing objective 3 of the study. The aim of this objective was to study the borehole performance by identifying aquifer parameters through pump testing newly drilled boreholes predict future water level trends and long-term operation of boreholes.

To achieve objective 3 of this study, pumping test data from 10 boreholes was acquired through performing a step down and constant discharge rate test. Data collected includes borehole depth, borehole diameter, static water level, depth to water. This was done to assess groundwater potential and to evaluate the effect of pumping on the groundwater system. Parameters estimated include Transmissivity (T), Storativity (S) and Specific yield (Sy). Pumping test data was analysed using applicable analytical solution based on their theoretical assumptions. The analysis was done using aquifer test pro software version 9.0.

4.2 Interpretation and description of Key results on aquifer parameter estimation

4.2.1 Constant discharge test and recovery results

The constant discharge and recovery test results are presented in table 4.1 and 4.2. From the data presented in table 1 and 2, it is evident that variable T and S values were obtained from different study sites with variable geological features.

The Macassar site tapping on the Malmesbury aquifer yielded T and S values of 2.53×10^{1} m ^{2}/day and 1.29×10^{-4} respectively. These results were obtained from the constant discharge test as shown in table 4.1. T value obtained from the recovery test was 23 m ^{2}/day. The drawdown and recovery plot is presented in figure 4.1.

The Gustrouw borehole, drilled on the Malmesbury aquifer produced T and S values of 1.77 m ^{2}/day and 3.87×10^{-4} respectively. The low T value is due to the occurrence of fine sand with interstitial clay materials and the hard shale deposits of the Malmesbury group rocks. Such geological materials have a high specific retention with a low porosity, hence the low transmissivity.

The Paarl borehole drilled on the Malmesbury aquifer produced T and S values of 1.48 m^2/day and 9.9×10^{-1} respectively as shown in table 4.1. The recovery test yielded T value of 2.19 m^2/day.

Grabouw borehole, also drilled on TMG aquifer produced a T and S value of 68 m^2/day and 3.9×10^{-1} respectively. These values were obtained from the constant discharge test as displayed in table 4.1. T value of 62 m^2/day was acquired from the recovery test as displayed in table 4.2. The T values obtained from both tests fall within the expected T range of the TMG aquifer.

Sonstraal borehole also taps on the Malmesbury aquifer. T and S values obtained from constant discharge test were 4.57×10^{-1} m^2/day and 3.32×10^{-1} respectively as shown in table 4.1. T value obtained from the recovery test was 4.39×10^{-1} m^2/day as shown in table 4.2.

T and S value of the Caledon borehole site is 2.51×10^{-1} m^2/day and 3.35×10^{-4} respectively, as shown in table 4.1. The T range of the TMG aquifer is 9 m^2/day to 400 m^2/day as suggested by several authors (Duah, 2010), therefore, the acquired T values fall outside the expected range. The T value of 2.85×10^{-1} m^2/day obtained from recovery as displayed in table 4.2 is like the T value obtained from the constant discharge test, therefore, the constant discharge test results can be considered as reliable.

Table 4.1: Constant discharge test results

Location	**Formation**	**Analytical model**	**Transmissivity (m^2/day)**	**Storativity**
Macassar	Malmesbury	Double porosity	2.53×10^{1}	1.29×10^{-4}
Gustrouw	Malmesbury	Double porosity	1.77	3.87×10^{-4}
Paarl	Malmesbury	Hantush	1.48	9.9×10^{-1}
Grabouw	TMG	Cooper Jacob	68	3.9×10^{-1}
Sonstraal	Malmesbury	Hantush	4.57×10^{-1}	3.32×10^{-1}
Caledon	TMG	Hantush	2.51×10^{-1}	3.35×10^{-4}

Table 4.2: Recovery test Results

Location	Formation	Analytical model	Transmissivity (m^2/day)
Macassar	Malmesbury	Double porosity	23
Gustrouw	Malmesbury	Double porosity	12.3
Paarl	Malmesbury	Hantush	2.19
Grabouw	TMG	Cooper Jacob	62
Sonstraal	Malmesbury	Hantush	4.39×10^{-1}
Caledon	TMG	Hantush	2.85×10^{-1}

The table below presents a summary of results from objective 1, 2 and 3 of the study.

Table 4.3: Conceptual model, Derivative analysis, and Parameter estimation results

Location	**Aquifer type**		**Analytical Model**	**Aquifer parameters**	
	Conceptual Model	**Derivative analysis**		**T (m^2/day)**	**S**
Macassar	Double porosity	Double porosity	Double porosity	2.53×10^{1}	1.29×10^{-4}
Gustrouw	Malmesbury	Double porosity	Double porosity	1.77	3.87×10^{-4}
Paarl	Semi-confined	Leaky	Hantush	1.48	9.9×10^{-1}
Grabouw	Confined	Confined	Cooper Jacob	6.8×10^{1}	3.9×10^{-4}
Sonstraal	Semi-confined	Leaky	Hantush	4.57×10^{-1}	3.32×10^{-1}
Caledon	Semi-confined	Double porosity	Hantush	2.51×10^{-1}	3.35×10^{-4}

Figure 4.14 to figure 4.20 presents the drawdown versus time graphs as measured from Macassar, Gustrouw, Paarl, Grabouw, Sonstraal and Caledon study site boreholes tapping on the Malmesbury and TMG aquifer. Graphs were plotted from the constant and recovery test carried out at the study sites. In all these curves, except for the Caledon study site, theoretical drawdown fitted perfectly with the measured drawdown. The theoretical drawdown followed a typical trend of increasing during pumping and decreasing during recovery. The Caledon site curve slightly differs in shape with that of the theoretical curve because the pump stopped working after 1000 minutes due to blockage and recovered

a little bit. This is shown in figure 4.19. These results suggests that the analytical models used for analysis were successful.

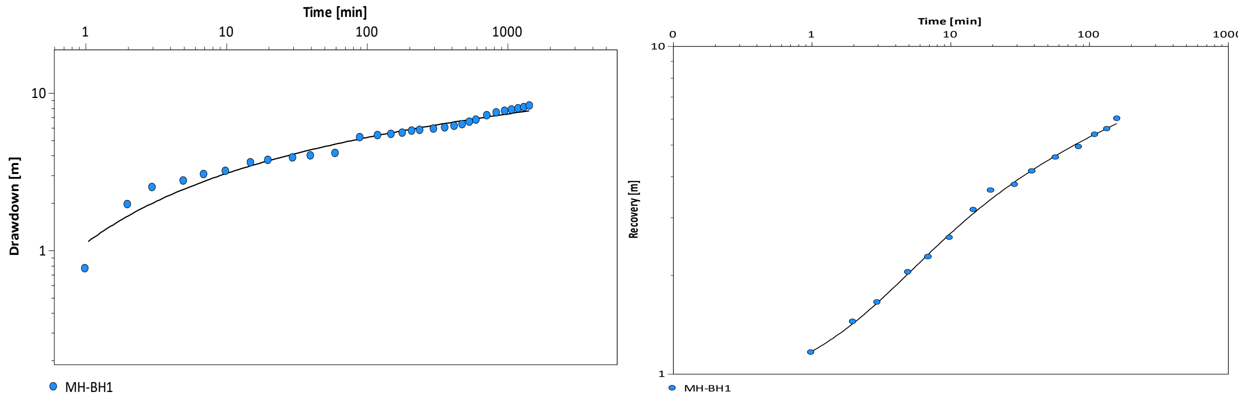


Figure 4.14: Drawdown vs time and recovery vs time plot of Macassar hospital borehole

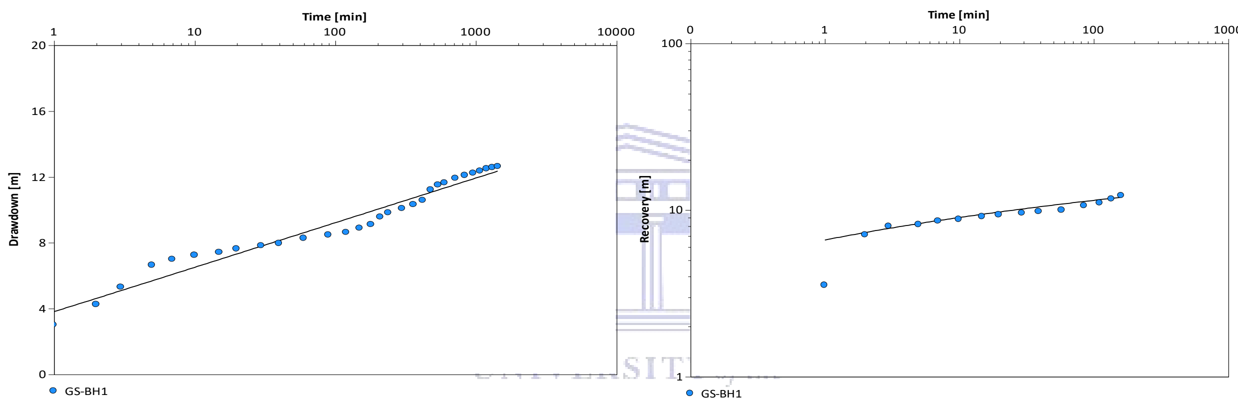


Figure 4.15: Drawdown vs time and recovery vs time plot of Gustrouw hospital borehole

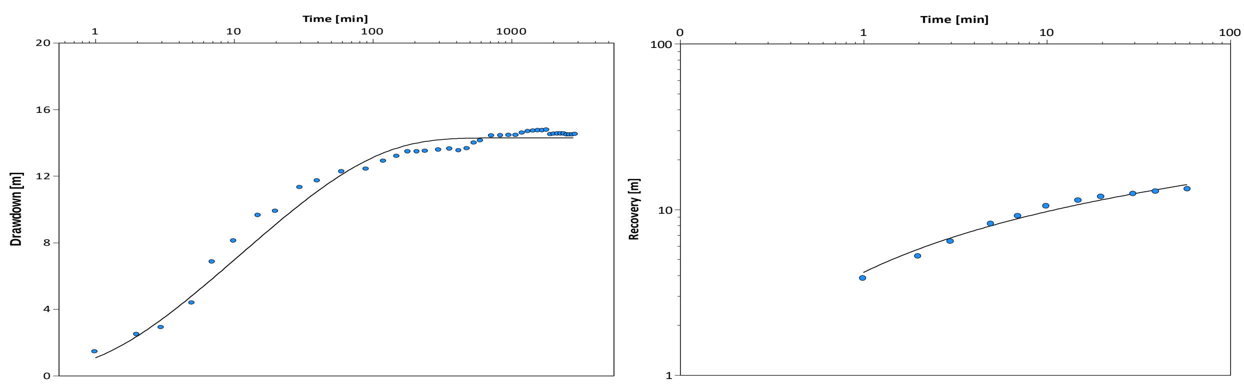


Figure 4.16: Drawdown vs time and recovery vs time plot of Paarl hospital borehole

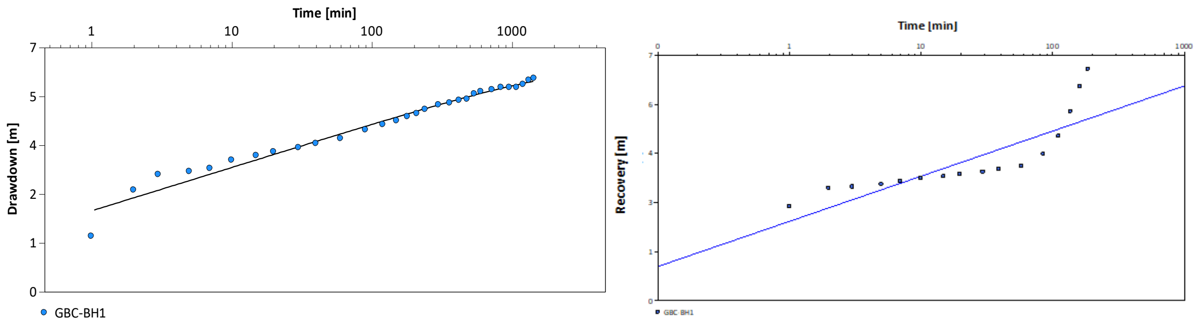


Figure 4.17: Drawdown vs time recovery vs time plot of Grabouw hospital site

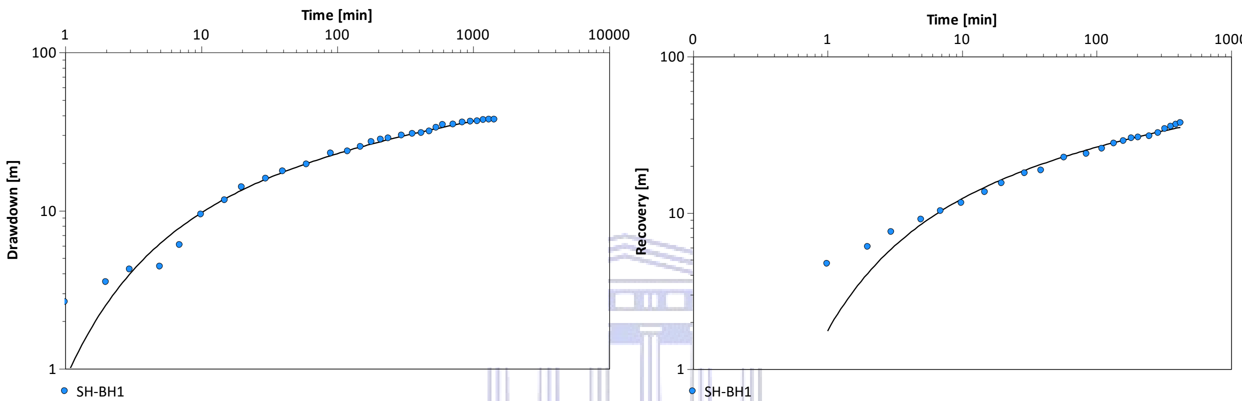


Figure 4.18: Drawdown vs time and recovery vs time plot of Sonstraal hospital borehole

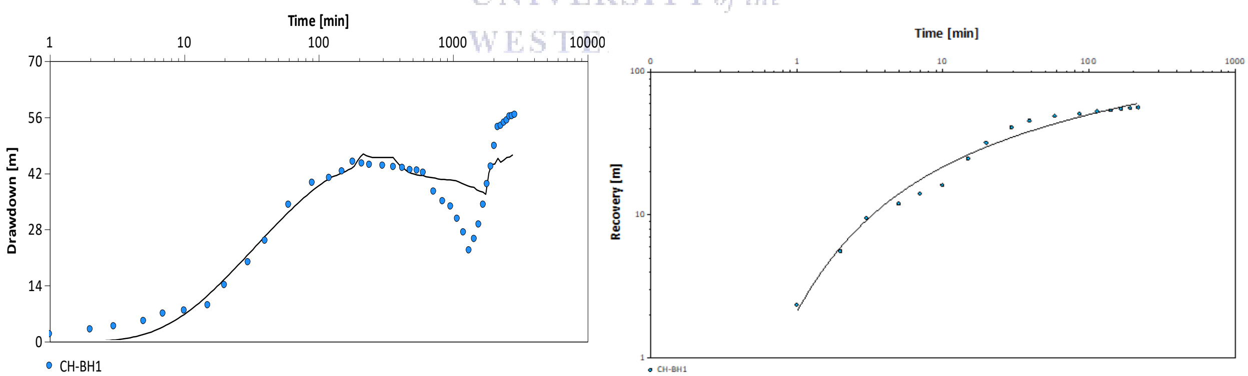


Figure 4.19: Drawdown vs time and recovery vs time plot of Caledon hospital site

4.3 Interpretation of results

Aquifer parameters were estimated using constant discharge and recovery data through application of the Cooper Jacob, Hantush Jacob and the Double porosity models. Table 2 presents results on aquifer parameter estimation using the fore-mentioned analytical models. The analytical models used for analysis were selected based on the site hydrogeological information, derivative analysis results and consideration of model assumptions, principles, strengths, and limitations. Parameters estimated include transmissivity and storativity. Transmissivity was considered as a parameter of interest because it assists in investigating the aquifers capacity to transmit water and it largely depends on the specific yield of the aquifer (Chen, 2003). This is crucial information used to identify sites where groundwater abstraction is possible (Birpinar, 2003).

The T value acquired from constant discharge and recovery test at the Caledon site was 2.51×10^{-1} m^2/ day and 2.85×10^{-1} m^2/ day, respectively. In reference to the TMG T range of 9 m^2/day to 400m^2/day suggested by several authors, estimated values fall outside the recommended T range of the TMG aquifer (Duah 2010). This could be due to the anisotropic nature of the TMG aquifer from borehole to borehole and from site to site, thus showing variation in hydraulic properties in different areas of study. The low T value could be due to low porosity nature of clay and consolidated quartzitic geological materials of the borehole site. According to T magnitude classification by Krasny (1993), Caledon site falls within class 5 with T values ranging between 1 m^2/day – 0.1m^2/day, representing an area of low T. Groundwater withdrawal in such an area is identified to be suitable for local water supply with limited consumption.

Constant discharge and recovery test results of Grabouw borehole site drilled on the TMG aquifer produced T values of 68m^2/d and 62m^2/d respectively, as shown in table 4.1 and 4.2. The estimated T value was found to be within the expected range of < 9m^2/day to 400m^2/day suggested by Duah (2010).

The T values were also estimated for newly drilled boreholes penetrating the Malmesbury aquifer at Macassar, Sonstraal and Paarl. T values estimated for these sites ranged between 0.39 m^2/day and 762 m^2/d. T values for Macassar fall within class 3 of Krasny's T classification thus implying that it has an intermediate T where groundwater withdrawal is suitable for local water supply in areas such as small communities. Low T values imply that it will take considerable time for groundwater recharge to occur in replacement of water withdrawn from aquifers. Furthermore, such T values are due to the occurrence of fine sand with interstitial clay materials and the hard shale deposits of the Malmesbury group rocks. Such geological materials have a high specific retention with a low porosity, hence the low transmissivity.

The estimated T value of Sonstraal borehole is 4.57×10^{-1} m^2/day and falls within class 5 of Krasny's T classification where groundwater withdrawal is suitable for local water supply with limited consumption.

Paarl borehole site had a T value of 1.48 m^2 /day which falls within class 4 of Krasny's T classification, implying that the site has a low T where groundwater abstraction is reliable for limited consumption or local water supply. The low T value of the Paarl study site is due to the occurrence of dominant fine sand, silt, clay, weathered granitic material, and the clay rock hornfels. These geologic materials have a low porosity and permeability thus resulting to low transmissivity.

Storativity values give an indication of the volume of water an aquifer can take or release from storage. It is a dimensionless quantity which varies with aquifer types. For an unconfined aquifer, it is defined as the volume of water that an aquifer takes or releases from storage per unit surface area of aquifer, per unit decline in hydraulic head (Younger, 2007). The storativity for unconfined aquifers ranges between 0.01 and 0.40 and ranges between 0.00005 and 0.005 for confined aquifers (Hamil et al., 1986; Freeze and Cherry 1979; Todd and Mays 2005). Higher storativity values imply that the aquifer can take or release high volumes of water. Low storativity values indicate that the aquifer can release low volumes of water and cannot be used for bulk water supply (Freeze and Cherry, 1979).

Storativity value of the Caledon borehole site is 3.35×10^{-4} as shown in table 4.1. In reference to storativity values suggested by Hamil et al., (1986) and Freeze and Cherry (1979), storativity values fall within the recommended range thus implying that borehole at this site taps within a confined aquifer system of the TMG. In reference to Jia (2007); recommended storage coefficient and specific yield of the Peninsula formation range between 10^{-2} to 10^{-5} and 5×10^{-3} to 1×10^{-4}respectively. The recommended specific yield and storage coefficient range of the Nardouw formation is 7×10^{-5} to 7×10^{-5} and 7.0×10^{-6} to 7.0×10^{-4} respectively (Jia 2007). Storativity value of the Caledon site falls within the suggested storage coefficient range of the Peninsula and Nardouw formation. This also confirms that the boreholes have been drilled in a confined segment of the TMG aquifer which agrees with the groundwater flow conceptual model of the study site. The low storativity values from the Caledon site are due to the presence of clayey and fine-grained sandy materials with TMG quartzite. Sstorativity is dependent on interconnectedness of fractures, therefore groundwater flows through interconnected fractures hence the estimated value also agrees with the TMG storativity range of 10^{-2} and 10^{-5} suggested by Rosewarne (2002), indicating bulk storage of groundwater within the fractured rock matrix. The aquifer system is highly permeable regardless of its fine-grained geological materials.

The Grabouw borehole site had a storativity of 3.9×10^{-1}as shown in table 4.1, therefore, it falls within the recommended storativity range of 0.01 and 0.40 for unconfined aquifers by Hamil et al. (1986) and freeze and Cherry (1979).

Sonstraal borehole taps on confined segments of the Malmesbury aquifer. This is since all storativity value of this site falls within the recommended storativity range for confined aquifers. In nature, leaky aquifers occur far more frequently than the perfectly confined aquifers. This agrees with the initial conceptual model, borehole log information and derivative analysis results.

Estimated storativity values from Gustrouw and Macassar borehole site are 0.34 and 0.49 respectively as shown in table 4.1. According to the storativity range suggested by Hamil et al. (1986) and Freeze and Cherry (1979), the boreholes are penetrating a shallow Malmesbury aquifer system. This agrees with the initial conceptual model and borehole log information.

Confining layers overlying or underlying an aquifer are rarely completely impermeable; instead, most of them leak to some extent (Kruseman de Riddler). This explains why most aquifers have been identified as confined based on the results from aquifer parameter estimation, which is in contrary to the results obtained from derivative analysis which classified confined aquifers as semi unconfined. This emphasises the fact that it is imperative to apply derivative analysis and understand the hydrogeology of the aquifer systems aquifer system prior estimating aquifer parameters as avoiding doing so may lead to misinterpretation of pumping test data.

4.4 Comparative analysis of results

A study by Zahid et al., (2018) evaluated deep groundwater system through analysis of pumping test data in South-eastern Bangladesh with the aim of monitoring groundwater potential to improve potable water supply. Analytical models used for analysis were selected based on consideration of assumptions and actual field conditions as suggested by the pattern of aquifer response to pumping. Hantush method was used to estimate transmissivity and storativity of 3224 m^2/day and 0.000215, respectively. Storativity agrees with the storativity of 0.000295 obtained from Macassar and Caledon borehole sites, thus suggesting that the aquifer should be confined to leaky confined in nature. This proves that the method applied to analyse pumping test data from Macassar and Caledon study sites was successful.

Hoppe et al., (2016) estimated aquifer hydraulic parameters using pumping test data from Nairobi area to determine aquifer vulnerability to heavy abstraction. Pumping test data from 84 boreholes was analysed using Cooper-Jacob and Theis Recovery analysis methods. The methods selected were used because they are commonly applied for pumping test data analysis. Data analysis involved fitting analytical solutions for pumping test to measured pumping test data using AQTESOLV software. From the hydraulic parameters estimated, it was concluded that the area has high transmissivity hence the aquifer has high maximum sustainable yields, and it was recommended that drilling should be avoided in aquifer sections with high transmissivity. Results like these were obtained at Grabouw borehole site thus proving that aquifers with high transmissivity have a high yield potential Grabouw.

From the results obtained, it has been identified that boreholes at Gustrouw and Macassar study sites may be appropriate for long-term water supply because they are located along the coast in a coastal aquifer. Grabouw borehole tapping on the unconfined part of the Malmesbury aquifer with a depth of less than 60m may be considered as suitable for local water supply in small communities because it is drilled on the shallow Malmesbury aquifer. Groundwater supply from the Paarl study site may be considered unreliable and less resistant to long term dry conditions because, it taps on the less fractured portion of the Malmesbury aquifer with a high component of clay and micaceous minerals which significantly limit groundwater flow. Moreover, this aquifer has low transmissivity and fractured ness, therefore it takes considerable time for the aquifer to recharge. This site may be considered as unreliable for long term groundwater supply. Groundwater supply from Sonstraal borehole may be suitable for limited use because groundwater recharge occurs at a low rate because of the low aquifer transmissivity. The borehole is therefore at a risk of depletion during dry seasons. The borehole located at Caledon is 150m deep and may be considered reliable for long term water supply because it has been drilled in the TMG aquifer with a depth of 50 – 2000m. Furthermore, the TMG aquifer is highly fractured hence it serves as a bulk supplier of groundwater in the Western Cape, therefore, the borehole drilled on the Caledon site may be considered as resistant to long term drought conditions. The Caledon site may be considered suitable for groundwater augmentation during long term drought conditions.

4.5 Evaluation of the study based on results

This chapter presented results on estimated aquifer parameters thus addressing objective 3 of the study. The main aim of this objective was to identify and predict if whether the boreholes are reliable enough for long term groundwater supply in hospital sites of the province. This objective argues that if reliable estimates of aquifer parameters are acquired, then the reliability of borehole for continuous groundwater supply will be known. Aquifer parameters estimated include Transmissivity (T), Storativity (S) and Specific yield (Sy). Pumping test data was analysed using applicable analytical solution based on geological information of the study site, derivative analysis results and the theoretical assumptions of analytical solution to be applied. The results revealed that Gustrouw and Macassar boreholes may perform long term because they are located along the coast, furthermore, they have been drilled in a zone where groundwater recharge occurs effectively due to its shallowness and highly transmissive geological materials.

Grabouw borehole taps on the unconfined aquifer at a shallow depth of less than 60m, therefore groundwater from these sites is suitable for local water supply in areas such as small communities and may be considered as reliable. The low transmissivity at the Caledon site also suggests that the aquifer is not reliable for long term groundwater supply; however, due its depth and highly fractured nature, groundwater withdrawal from this site should be considered as reliable and may be resistant to long term dry conditions. These results were considered as reliable and there are no reasons to doubt findings because studies on aquifer parameter estimation from pumping test data have been reviewed and were compared to the current study. It has been identified that the results from other scholars do agree with those of the current study, thus suggesting that the results are reliable.

4.6 Implication of results for practice and policy

Findings have contributed Knowledge enhancement of aquifer hydrogeological characteristics of the TMG and Malmesbury aquifer. This will prevent long term effects of abstraction from the aquifer which may impact on the storage fracture networks thus resulting to borehole failure. Furthermore, it will help inform management plans which will assist in ensuring that groundwater from shallow boreholes is not heavily abstracted and that alternative sources of water are identified to serve as a backup plan in case groundwater from boreholes is depleted. Furthermore, dry wells will be avoided, and high yielding boreholes will be constructed to supply the needed groundwater quantity for supply.

5.1 Refined hydrogeological groundwater conceptual model

A hydrogeological conceptual model is a pictural presentation developed to provide an initial framework to explain the groundwater flow system of a study area, incorporating geological and hydrogeological data into a cross section or block diagram (Odiyo et al., 2016). The incorporation of hydrogeological data with the geological understanding has always been vital for development of conceptual and numerical groundwater models. The development of a 3D hydrogeological conceptual model brings advantages by capturing more clearly the geologist's structural interpretations such that the geology is not oversimplified in the following process of modelling (Bricker et al., 2014).

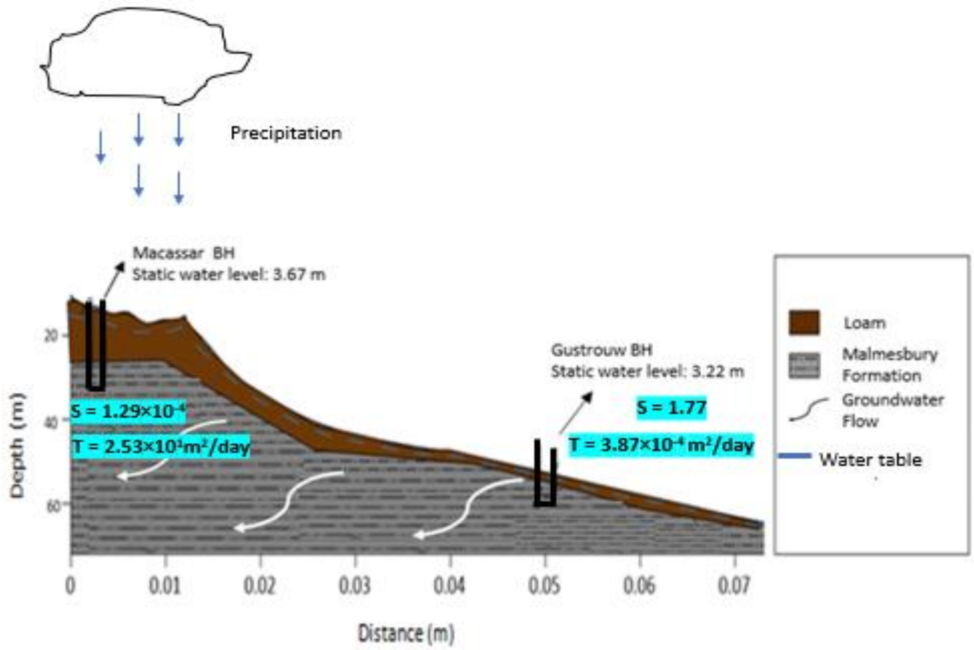
Hydrogeological information including topography, geology, aquifer thickness, water table, aquifer parameters, flow regimes and boundary conditions have been consolidated and used as additional information to produce an updated or refined groundwater flow conceptual. Development of this conceptual model was an iterative process which led to knowledge gap identification which will require further data collection for improvement, therefore, the conceptual model requires updating as more data becomes available.

5.2 Hydrogeological setting

A refined hydrogeological conceptual cross section of Maccassar and Gutrouw study sites is presented in figure 4.20 below. The diagrams shows that the prevailing geology at the Macassar site is Malmesbury with the uppermost layer being the Springfontein formation. The Malmesbury formation, forming the bedrock is characterised by hard shale deposits. The borehole is drilled along the coast in an aquifer characterized by shallow water table conditions and highly conductive gravel-sand hydrogeologic units. Such hydrogeological characteristics are good for groundwater yield and abstractions Gomo et al. (2013), Musekiwa et al., (2011). Groundwater flow is from inland and flows in a south-westerly direction towards the coast, where it discharges into the ocean. These boreholes are linked to meteoric water.

The borehole drilled at Gustrouw study site produced T and S values of 1.77 m^2/day and 3.87×10^{-4} respectively. Low T value is due to the occurrence of fine sand with interstitial clay materials and the hard shale deposits of the Malmesbury group rocks. Such geological materials have a high specific retention with a low porosity, hence the low transmissivity.

Macassar site yielded T and S values of 2.53×10^{1} m^2/day and 1.29×10^{-4} respectively. These results were obtained from the constant discharge test as shown in table 4.1. T value obtained from the recovery test was 23 m^2/day.



igure 4.20: Refined hydrogeological conceptual cross section of Maccassar and Gutrouw study sites

A refined hydrogeological conceptual cross section of Paarl and Sontraal study sites is shown in figure 4.21 below. Based on the 1:1000 000 geological map of South Africa from the Council of Geoscience; Paarl borehole taps on a fractured rock aquifer (Musekiwa et al. 2011). The site is overlain by a thin layer of highly weathered unconsolidated fine to medium sand with clay and silt particles which can be categorized as alluvial deposits of the Enon formation. Water is trapped in pore spaces of unconsolidated alluvium deposits forming the primary aquifer. This formation is underlain by a thick layer of unconsolidated silt and clay mostly dominated by the clayey material. The underlying bedrock is comprised of grey-black consolidated shale of the Malmesbury formation that has been metamorphosed into hornfels. Groundwater is trapped in joints, fissures, and fractures at a depth of approximately 36m of the Malmesbury formation forming the secondary aquifer (Engelsman et al 2000).

The pumping test at Paarl site yielded T and S values of 1.48 m ^{2}/day and 9.9×10^{-1} respectively. The recovery test yielded T value of 2.19 m ^{2}/day. Sonstraal borehole also taps on the Malmesbury aquifer, and it produced T and S values from constant discharge test of 4.57×10^{-1} m^2/day and 3.32×10^{-1} respectively. T value of 4.39×10^{-1} m^2/day as obtained from the recovery test.

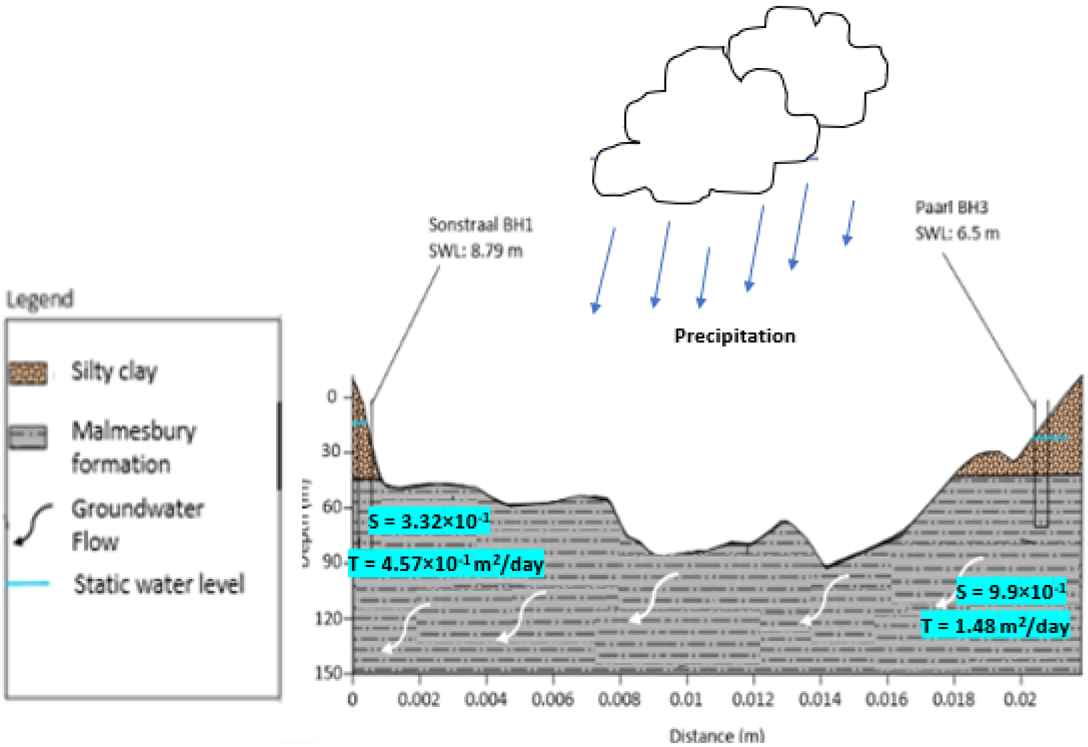


Figure 4.21: Refined hydrogeological conceptual cross section of Paarl and Sonstraal study site

Chapter 5: Conclusion and recommendations

The main objective of the study was to determine reliability of the application of derivative analysis and aquifer parameter estimation to refine a hydrogeological conceptual model. The study aim was achieved using geological information, derivative analysis of pumping test data and aquifer parameter estimation to produce a refined hydrogeological groundwater conceptual models of the study sites targeted for groundwater augmentation.

Objective 1 focused on conceptualization of aquifer system using geological information from borehole data and the existing conceptual models. The aim of this objective was to understand the subsurface geology of the borehole sites. Results revealed that the storage coefficient of the TMG aquifer is dependent on the interconnectedness of fractures, therefore groundwater flows through interconnected fractures hence the aquifer system is highly permeable regardless of its fine-grained geological materials. From the findings, it was concluded that the TMG aquifer has a bulk water supply due to its fractured nature whilst the Malmesbury formation has a limited water supply because it is less fractured thus resulting to a delay in groundwater flow from aquifer to borehole. It is therefore recommended that the TMG aquifer should be targeted for bulk groundwater supply. On the other hand, geological results revealed that even though the Malmesbury is known as a low yielding aquifer, there are zones with bulk water supply such as the Paarl site due to high yielding fractures in the bedrock, hence it should be targeted for reliable groundwater supply.

Objective 2 focused on derivative analysis of drawdown data with the aim of determining aquifer types, flow regimes and boundary conditions using drawdown derivative analysis to understand the complex aquifer heterogeneity influencing groundwater flow to wells. From the findings, it was revealed that the boreholes drilled on the Malmesbury and TMG formation tap on a double porosity and semi-confined aquifer. Borehole sites which portrayed double porosity aquifer behaviour include Macassar, Gustrouw. Paarl, Sonstraal, Grabouw and Caledon sites portrayed a fractured and semi-confined aquifer behaviour. The double porosity aquifer behaviour was characterised by delayed yield identified from the declension drawdown derivative towards late time and fracture dewatering. Flow came from storage in fractures, followed by a transition period whereby the matrix blocks feed their water to fractures. Towards late time of pumping, water was withdrawn from storage in both fractures and matrix blocks. The semi-confined aquifer behaviour was observed when the cone of depression reached a recharge boundary. The leaky aquifer case was distinguished from a constant head case by looking at the shape of the derivative. The derivative tends towards zero earlier in the case of leaky aquifers and much faster than in the case of a constant head boundary. Based on the results, it is concluded that the derivative analysis method helped identify flow regimes and discern boundary conditions. This in turn provides useful information for conceptualising aquifer characteristics, furthermore, it also facilitates the selection of an appropriate analytical model to evaluate and understand the hydraulic parameters of the aquifers.

Objective 3 focused on aquifer parameter estimation with the aim of understanding and predicting borehole performance and reliability for groundwater supply. Findings revealed that transmissivity values from the Caledon site are outside the expected range of 9 m2/day to 400 m 2/day suggested by several authors (Duah 2010). Transmissivity values for borehole 1 and 2 of the Caledon site is 0.77 m/day and 0.11 m2/ day, respectively. The values are outside the suggested range, and it has been assumed that this is due to the anisotropic nature of the TMG aquifer from borehole to borehole and from site to site, hence the variation in hydraulic properties from the different study areas. Furthermore, the results revealed that low transmissivity values were assumed to be due to the low porous nature of clay and the consolidated quartzitic geological materials where boreholes have been drilled. However due to the fractured nature of the TMG aquifer, it has been proven to have a bulk water supply for various uses within the Western Cape. Low storativity values were obtained from the Caledon site and this was assumed to be due to the presence of clayey and fine-grained sandy materials with TMG quartzite. Transmissivity values for Gustrouw, Macassar and Grabouw sites have an intermediate transmissivity where groundwater withdrawal is suitable for local water supply in areas such as small communities. Sontrsaal site had the lowest transmissivity indicating that the groundwater abstraction at these sites is suitable for local water supply with limited consumption. Storativity findings revealed that Gustrouw and Macassar boreholes penetrate the shallow and unconfined alluvial aquifer system of the Malmesbury formation thus agreeing with the initial hydrogeological groundwater conceptual model and borehole log information. Storativity results from Worcester borehole site imply that boreholes penetrate the unconfined Malmesbury aquifer as they fall within the recommended storativity range for unconfined aquifers. This agrees with the site geological information and derivative analysis results. Sonstraal borehole taps on the confined segments of the Malmesbury aquifer. This was identified from the fact that all storativity values for these sites fall with the recommended storativity range for confined aquifers. In nature, leaky aquifers occur far more frequently than the perfectly confined aquifers.

Objective 4 focused on developing a refined hydrogeological groundwater flow conceptual model. The aim of this objective was to produce a detailed conceptual model with reliable hydraulic parameters and geological features. Based on the geological information of the area and hydraulics data with aquifer parameters, a conceptual model was developed which gave a clearer picture of the study area. From the results, it is concluded that shallow boreholes drilled on the Malmesbury formation may not be considered as reliable because they may easily get depleted by continuous groundwater abstraction due to the shallow nature of the aquifer.

Conclusion

Based on these findings, the study concluded that Gustrouw and Macassar boreholes are suitable for long term water supply because they have been drilled along the coast in a coastal aquifer. Grabouw borehole taps on the unconfined portion of the Malmesbury aquifer at a shallow depth of less than 60m, therefore groundwater from this site may be suitable for local water supply in areas such as small communities and may be considered as reliable. Groundwater withdrawal from Sonstraal borehole is suitable for water supply with limited consumption because it will take a considerable time for the aquifers to recharge water into wells removed during pumping due to the low transmissivity values, therefore the borehole may be vulnerable to depletion during dry events. Groundwater supply from Paarl study site may be considered as unreliable for long term water supply. This is due to its low fractured-ness and transmissibility caused by a high component of clay and micaceous minerals which significantly limit groundwater flow. It also takes a considerable time for aquifers to recharge water withdrawn from wells during pumping, therefore, this site is considered suitable for local water supply through smaller withdrawals. The Caledon site suggests that the aquifer is reliable for long term groundwater supply due to its depth and highly fractured nature. It is therefore considered to be a suitable site where boreholes resistant to long term dry conditions may be drilled.

Recommendations

Detailed research on recharge mechanism and hydrogeology of the Malmesbury aquifer is recommended because limited research has been conducted on those subjects. Knowledge of aquifer hydrogeological characteristics will prevent long term effects of abstraction from the aquifer which may impact on the storage fracture networks and may result to borehole failure. In depth research on the geology of the Malmesbury aquifer is recommended to identify fracture and fault zones within the aquifer, which may serve as groundwater exploration targets. This will help inform management plans which will assist in ensuring that groundwater from shallow boreholes is not heavily abstracted and that alternative sources of water are identified to serve as a backup plan in case groundwater from boreholes is depleted. Furthermore, dry wells will be avoided, and high yielding boreholes will be constructed to supply the needed groundwater quantity for supply.

It is recommended that the TMG aquifer should be targeted for groundwater augmentation due to its high depth and bulk water supply; unlike the Malmesbury aquifer which may get depleted should drought conditions hit the province. Studies on groundwater recharge of the aquifer need to be conducted as it is an important component in aquifer characterisation. Furthermore, detailed research on groundwater flow system using tracer methods like isotopes and numeric models is essential, more especially on the Malmesbury aquifer. In return, this will assist groundwater managers with informed decision making on groundwater exploration targets.

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