GROUNDWATER RESOURCE EXPLORATION WITHIN THE INNER-CITY OF JOHANNESBURG

Ondela Tywakadi

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DECLARATION

I declare that this research report is my own, unaided work. It is submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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(Signature of candidate)

19th day of October (year) 2020

ABSTRACT

This study examined the hydrogeological characterisation of the Johannesburg inner-city. Residents reported a high water table that has resulted in groundwater seepage into building basements, posing a safety threat and limited functionality of these structures. Although this high groundwater table triggered this investigation, it took a deeper and broader approach by seeking to quantify the amount of groundwater resource that is available to be used to supplement the existing municipal supply. The study also aimed at establishing long-term sustainable abstraction rates and viable fit-for-purpose use of the available groundwater. The study then evaluated the abstraction rates against the water table response in order to achieve a safe water table level at which groundwater seepage into building basements does not occur.

The methodology employed included assessing and verifying the number and distribution of buildings affected by groundwater seepage. Information was gathered by circulating a survey in the form of a questionnaire to a network database of property owners and managers. Field work, in the form of drilling and testing boreholes, and subsequent data processing were carried out to characterise the aquifers and establish the quantity of the resource. In order to determine possible uses of the groundwater, water chemistry testing was carried out. The characteristics and recharge dynamics of the aquifers that were established served as inputs into a numerical model which estimated the quantity of groundwater that can be sustainably abstracted for utilisation, while ensuring the water table is sufficiently suppressed.

An estimated 2.47 million-m^3 (or billion-litres) of groundwater is available as a total yield potential within the Johannesburg inner-city. This water can be sustainably withdrawn from the ground at a safe yield (abstraction rate) of over 56 million- litres per annum (56 902 m^3/a) from the nine drilled boreholes. The system response corresponding to this abstraction rate is predicted to cause a 2.3m decline in the water table level compared to the current scenario. This desired pumping scenario would suppress the water table level to be at an average of 8.6m below ground. The average basement depth in the Johannesburg inner-city is 8m below ground and hence, most building basements would consequently not be flooded under this scenario. Currently, 60% of building basements are subjected to the risk of flooding, and this would reduce to 30%, which is made up of those deeper than 9m.

The current water demand in the Johannesburg inner-city is approximated to be 80 Ml/day. Therefore, the estimated groundwater yield to supplement the municipal supply is insignificant (0.2%), and does not justify an investment into retrofitting the groundwater infrastructure into the bulk infrastructure system. Thus, developing a groundwater source infrastructure for bulk water supply purposes is not volumetrically viable in the case of Johannesburg inner-city, but can be beneficial for building strategic reserves and resilience into the system. It is recommended that in future, fine-tuning and continuous calibration of the numerical model should be carried out when the boreholes are in operation. Further research is also required to examine the aquifer geo-mechanics in order to assess the risk of land subsidence with decreasing water table levels, especially in a possible future scenario of over-exploitation of the aquifer.

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1. INTRODUCTION

1.1 Background

The commercial property owners of the Johannesburg Business Forum approached the City of Johannesburg (CoJ) municipality, citing a problem of groundwater seepage into numerous buildings that are located in the central business district (CBD) and the surrounding areas of Braamfontein, Doornfontein and Newtown. These suburbs comprise the 'inner-city' of the City of Johannesburg Metropolitan. In most of the properties, the seepage is allowed to discharge into the storm water drainage inlets but its amount is yet to be evaluated. Property owners are concerned about the high running costs as well as maintenance costs due to the ingress of the water. Conversely, there is a risk that the high capital costs of retrofitting for groundwater reclamation would not have a good return on investment if the quantity of water is insufficient.

The CoJ recognises that groundwater is a potential water source that can supplement the potable water supply to the city. As a result, the Environment and Infrastructure Services Department (EISD) embarked on a groundwater potential feasibility study. The first phase sought to determine the areas with the highest potential for groundwater reclamation within the city as well as to identify what that groundwater can be used for (e.g. irrigation, filling of swimming pools, toilet flushing, cooling, etc.). In the second phase of the project, EISD undertook to drill and develop boreholes. The boreholes were positioned in close proximity to swimming pools, recreational parks as well as sports fields, which constitute nodes of high water demand. It was envisaged that if the groundwater quality was adequate, it would be used to refill the pools and/or irrigate the fields and thereby reduce the dependence on the municipal water supply.

In 2011, the CoJ had a population of approximately 4.435 million people residing in 1.1 million households (census 2011). Based on an estimated annual growth rate of 3.2%, the water demand of the city is expected to increase considerably in order to meet the city's economic, social, commercial and industrial activities. The city is the biggest water consumer out of the Vaal River Catchment and accounts for 40% of the volume of water abstracted by Rand Water out of the Upper Vaal River Catchment. The Department of Water and Sanitation has approved a Water Use Licence that requires Rand Water to abstract 12% less volume of the focused demand for 2020. Consequently, water conservation and water demand management has become an increasingly important aspect, in addition to finding new water sources, such as groundwater that can be used to augment the city's supply.

On the basis of the above (i.e. high groundwater table within the inner-city and increasing demand for potable water), a more sustainable solution is sought. To address this requires quantification of the available groundwater resource that can be economically and sustainably abstracted in a way which takes into account the characteristics of the aquifer in the study area.

1.2 Study Area Description

The study area is located within the City of Johannesburg in the Gauteng Province of South Africa. The area of interest lies in the inner-city comprising the CBD, Braamfontein, Doornfontein and surrounds of Johannesburg Metropolitan (approximately 28.0457° E, 26.1986° S), indicated by the red square in ***Figure 1***. The area's average ground level is 1747 metres above sea level and its mean annual precipitation is approximately 600mm. Although the study area is situated on a watershed, it is predominantly (two thirds) siting on the C21D quaternary sub-catchment of the Upper Vaal River Catchment.

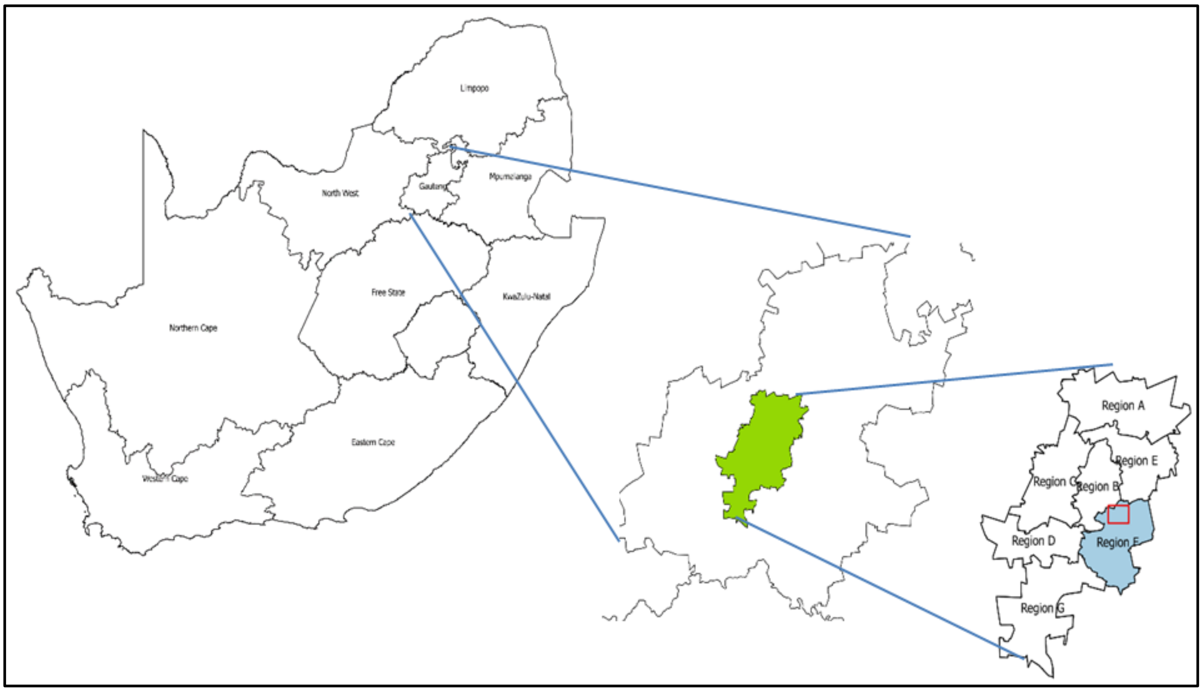

Figure 1: Location of the study site (red square) in City of Johannesburg, Gauteng Province, South Africa

The study area mainly lies on the 2.8 Ga Witwatersrand Basin found on the Kaapvaal Craton, which comprises one of the world's largest gold placer deposits. The basin is sub-divided into three gold bearing basins namely: West Rand, Central Rand and East Rand. The City of Johannesburg is located over the mined out gold deposits of the Central Rand.

The area is a built-up urban metropolitan that is densely populated and mostly consists of commercial residential and office-block properties. The municipal water supply to the area mainly relies on surface water for both domestic and commercial activities. There is a relatively new development of urban agriculture on roof tops, which is also mainly dependent on the municipal water supply, with scattered usage of harvested rainfall water.

1.3 Problem Statement

This research seeks to solve in a sustainable manner the problem of groundwater seepage into building basements in the inner-city, while at the same time developing the knowledge of the hydrogeological setting of the aquifer(s) within the study area. Knowledge of the quantity and quality of the available groundwater in the area would enable management of the resource in such a way that it is not depleted. Furthermore, appropriate uses of the groundwater can be utilised to augment the potable water supply, which is under stress due to large and increasing demands. Thus, the primary focus (or problem statement) of this research project is: Quantification of available groundwater in the Johannesburg inner-city, for sustainable domestic, commercial and agricultural uses by inner-city properties and residents, while maintaining safe water table levels.

1.4 Aim and Objectives

The main objective of this research is to determine the quantity of groundwater that is available in the study area in order to evaluate how much water can be abstracted in a sustainable manner, while ensuring that the groundwater table is at a safe level that minimises groundwater seepage into building basements.

The specific objectives of this research are the following:

- Characterisation of the aquifer(s) in terms of the hydrogeological environment and flow regime.
- Conceptual modelling to ascertain the extent of the aquifer(s) in the Johannesburg inner-city.
- Numerical modelling of the groundwater resource system in order to estimate the long term sustainable abstraction rates.
- Identifying the best use of the abstracted groundwater resource.

1.5 Key Research Questions and Scope

The CoJ seeks to adopt a framework that will guide the development and monitoring of groundwater use as a complementary resource in the city. The key research questions to be answered by this project include:

1) How much groundwater is available for safe abstraction within the Johannesburg inner-city, while ensuring safe water table levels for building basements?
2) What are the characteristics and recharge dynamics of the aquifer(s) underlying the Johannesburg area?
3) What would be the economically viable usage of the abstracted groundwater?

This research project focused on answering the above questions for the specific study area of the Johannesburg inner-city, defined as Johannesburg CBD, Braamfontein, Hillbrow, Berea, Yeoville, Doornfontein, New Doornfontein, Betrams, Troyeville and Jules. The defined study area will hereafter be referred to as the 'inner-city'. Nine (9) boreholes were drilled within the inner-city and the data were analysed and used in the development of a numerical model to characterise the groundwater flow.

1.6 Significance of this Research

This research is important because no hydrogeological studies have specifically focused on the inner-city before and hence this work will contribute to the knowledge base of characterising the aquifers in inner-city of Johannesburg. This study will also help in understanding how abstraction quantities will affect the aquifer. Importantly, this study will add to the hydrogeological knowledge base of the area and potentially contribute to better and more responsible utilisation of the groundwater resource.

1.7 Structure of the Thesis

Chapter 1 introduces the study area, context and background of the research project, problem statement, key research questions and justification.

Chapter 2 looks at the literature review with emphasis on the approaches used to characterise aquifer systems and groundwater flow.

Chapter 3 presents the methods used for hydrogeological characterisation in this study.

Chapter 4 provides the obtained results, which are relevant to the key research questions.

Chapter 5 discusses the findings and implications thereof.

Chapter 6 presents the conclusions and recommendations.

Appendix A provides the sample of the questionnaire template used.

Appendix B presents a summary of the sites visited and verified.

2. LITERATURE REVIEW

The literature reveals that different approaches used to characterise aquifer systems dependent largely on availability of data. The various approaches and/or steps used in aquifer characterisation include geologic setting assessment, hydraulic tests, geochemistry and tracer tests, surface fracture surveys, remote sensing, and using Digital Elevation Model (DEM) and Geographic Information Systems (GIS) data amongst others. Usually, a combination of two or more of these approaches is employed to examine and understand a pool of hydrogeological factors at play. The typical hydrogeological factors that control groundwater occurrence and its sustainable development include surface and bedrock lithology, geological structures, geo-chemical status and recharge dynamics.

To further understand the hydrological factors that govern a particular system, there are also various groundwater modelling techniques used according to function and intended use of the model. In using groundwater as a water supply source, proper monitoring of water levels in and around a particular basin is required. This monitoring can be done through a mathematical model that would be able to predict changes in water levels given different pumping regimes and recharge scenarios that can arise. To do this, a numerical model that speaks to the specific conditions of the site would need to be developed and calibrated. A borehole monitoring programme that would physically measure and monitor the water levels in real-time should also be established for cross-reference monitoring and model calibration purposes.

Knowing the quantity of available groundwater is important as it enables the local authority to effectively manage the resource by monitoring its use and also developing strategies to regulate the use thereof. Hence, this part of the study will explore the means that can be used to carry out the quantification of groundwater availability. The subsequent sections describe the different approaches to aquifer characterisation, conceptual model development and modelling techniques that have been adopted in previous studies in order to develop an understanding of a groundwater flow system.

2.1 Characterisation of aquifers

2.1.1 The geological setting assessment

The geological setting assessment is carried out to gather information relating to an overview of the geology, geomorphology/ weathering and stratigraphy of the study area. The geological setting would generally be expressed by the varying combinations of the geology, extent of weathering and arrangement of stratigraphy together with the effective rainfall that contributes to the recharge dynamics. In many instances the recharge dynamics are impacted by land use patterns and changes (which affect surface infiltration) and water infrastructure leakages (artificial recharge), amongst other factors. According to MacDonald et al. (2012), these combinations then create the basis on which groundwater occurrence manifests and is usually in a wide spectrum of "complex hydrogeological environments differing in aquifer transmissivity, effective porosity, saturated thickness of aquifers and groundwater recharge".

Pétré et al. (2016) emphasize the importance of having a detailed understanding of the aquifer hydrogeological dynamics in order to carry out sound groundwater resource management. This understanding can lead to a comprehensive representation of the aquifer where numerical models, which enable quantification of groundwater changes, are developed (ibid). To have a clear picture of the geological setting, data must be as localized to the specific site as much as possible.

The geological data can be gathered from a wide range of sources, including academic and commercial literature with borehole data, geological field surveys, drilling logs, maps, preliminary hypothesis on the genesis of the formations, etc (Rivard et al., 2008; Chiocchini et al., 2010; Abiye, 2011; Rahi and Halihan, 2013; Rodríguez-Rodríguez et al., 2007; Pétré et al., 2016; Hoque et al., 2017). This data then enables delineation of groundwater potential zones and gives an idea of aquifer types that may be found in the area. A census of the springs and boreholes which may be located in the study area should also be conducted to provide more details and build a mental picture of the hydrogeological setting. Springs may originate via lateral contact between the relatively high permeable and less permeable complexes (Saroli et al., 2017).

It is important to understand the fracture systems in fractured crystalline rock masses. The faults and large fractures (with their associated respective connectivity) usually have higher values of hydraulic transmissivity, thereby controlling flow within the rock and the permeability of the rock mass through preferential flow paths (Hao et al., 2008; Burbey, 2008; Bang et al., 2012; Shapiro et al., 2015). Knowledge of the geological setting gives an insight into potential aquifer systems and likely groundwater boundaries. Borehole drilling thereafter provides a greater insight into the character of the aquifer.

2.1.2 Detection of fracture zones

Boreholes that produce significant amounts of water usually occur in close proximity to secondary permeability features such as fractures or fault zones. It is therefore worthwhile to locate the secondary permeability features before drilling boreholes in order to avoid drilling unproductive boreholes, where possible. These are usually found in non-fractured zones especially in semi-arid regions. Various methods are used to detect fractures including: seismic, sonic and ultrasonic, electrical, radar, and satellite airborne imaging methods, amongst others. Electromagnetic profiling is also one of the techniques that has been widely employed, and was also used during the geophysics testing in the current study. It is based on the principle of electromagnetic induction, where alternating current in a transmitter coil induces very small currents in the earth and produces a time-varying magnetic field (Ugwu and Nwosu, 2009). The instruments used can cover extensive distances and hence wide areas, for example, a terrain conductivity meter that was used by Ugwu and Nwosu (2009) could traverse up to 1000m with an inter-coil separation of 20m, taken normal to the strike.

Rahi and Halihan (2013) showed that studying fracture occurrence in aquifers using harmonic analysis is a beneficial and cost effective way of determining the aquifer type (confined, semi-confined or unconfined), especially where pumping tests may yield inconclusive results. Black et al. (2017) highlighted that studying fracture occurrence is especially critical in sparsely fractured crystalline rock formations where there are low rates of tracer recovery. Bang et al. (2012) presented the discrete function network (DFN) model which relies on stochastic realisation of the fracture systems. They suggested that the approach provides an improved representative elementary volume (REV) and overall hydraulic properties in fractured rock masses.

Lee and Kim (2015) state that it is important to provide information that relates to the hydraulic properties of the fractures in order to not only identify “a relatively large-scale open fractured or weathered zone that is possibly permeable” but also rather to identify “the small-scale permeable fractures serving as pathways for groundwater flow”. These authors introduce a Self-Potential (SP) logging method that can effectively detect the hydraulic activity of the observed fractures (ibid). Further research is said to be ongoing insofar as the validity of the predictions inferred from the SP method.

2.1.3 Assigning aquifer parameters

Several aquifer properties are used to characterise the identified hydrostratigraphic units, including porosity, specific yield, transmissivity, aquifer thickness, etc. Aquifer parameters such as hydraulic conductivity and storage coefficient are the key properties in characterising the aquifer formation and their knowledge is necessary for optimal groundwater management (Xiang, 1996; Chang et al., 2008; Scorpo et al., 2017). Water levels and flow direction are also determined as they contribute to the comprehensive representation of the groundwater system conceptual model. The aquifer properties give an indication of how much groundwater is actually available for use and how that quantity can be effectively managed for long term sustainability.

Chang et al. (2008) define hydraulic conductivity as the most important hydrogeological parameter for describing the ease with which water flows through a porous medium. The hydraulic conductivity relates to the ability of the rock or soil to transmit groundwater. Hydraulic tests are conducted to determine the hydraulic conductivity of the geologic material. Tests include laboratory methods, auger-hole tests, and pumping tests of boreholes (Todd and Mays, 2005). Pumping tests of boreholes is the most reliable method for estimating aquifer hydraulic conductivity and storage coefficients, with which future declines in groundwater levels associated with pumpage can then be calculated (Maréchal et al., 2003; Todd and Mays, 2005). Common pumping tests include constant rate tests, step-drawdown tests and recovery tests.

In the recent decade, it is important to note that researchers have raised concerns that relate to the validity of the traditional pumping tests in estimating aquifer parameters (e.g. Maréchal et al., 2003; Yeh and Lee, 2007; Rahi and Halihan, 2013; Ashjari, 2013). Some have pointed out that the commonly used solutions of Theis or Cooper and Jacob are too inaccurate to represent inherently heterogeneous aquifers as homogeneous, and thus subjecting current water resource management strategies to great uncertainty (Yeh and Lee, 2007). Ashjari (2013) points out difficulties associated with conducting pumping tests, suggesting that the limitations provide poor reliability on the data for parameter estimation. Maréchal et al. (2003) claim that the complexity of flows through fractures in fractured hard rock aquifers (such as granite, gneiss, basalt) makes the use of classical techniques such as Theis and Jacob methods inadequate. They argue that in hard rock contexts the assumptions of homogeneity and isotropy are not coherent with the reality and as a result, presented four different methods (Neuman, Gringarten, Warren and Root, and Baker theory) that are “more suitable” for different hard rock aquifer scenarios and types (ibid).

The counter argument is that although there are some shortcomings, the remarkably observed alignment between measured field data and the theoretical models of ideal homogeneous aquifers justifies the use of the conventional pumping tests, especially in water supply investigations (Butler, 2008). To overcome some limitations, Ashjari (2012) introduced a method that enhances the traditional tests where only the residual drawdown (drawdown during recovery) data is used to estimate transmissivity and storage coefficients without assuming equality of storage coefficients.

2.1.4 Understanding groundwater quality

Geochemistry techniques are used to assess the groundwater chemistry and other selected hydraulic parameters (mainly mass transport parameters) in order to carry out site-characterisation. The techniques can be used to determine the quality of the water, the age of the water and the circulation patterns amongst other parameters. Abiye (2011) used the geochemistry techniques to trace the origin of the groundwater within the crystalline rocks of the greater Johannesburg area. In the study, geochemical and environmental isotope variables were used to provide information regarding the source of the groundwater, the dominant circulation mechanism and the flow depth. Abiye (2011) used a groundwater database and some field verification on accessible water points to produce variation diagrams of ion concentration with depth and then measured isotopes before using the principal component analysis to characterise the groundwater of the area. A similar study was done in Mexico by Lagarde et al. (2014) where the researchers determined the recharge dynamics of different springs by using chemical properties such as ion concentrations, water temperature and carbon dioxide pressure in the hole and depth of circulation. The specific recharge aspects explored in the study were namely: the source of the water and the recharge elevation.

Amongst several other techniques used, injected tracer methods can be used to indicate groundwater flow direction and velocity through a given aquifer. Injected tracer methods are especially useful to understand the groundwater flow dynamics through fractures (Rangarajan et al., 2014). Borehole tracer tests can also be employed to test the hydraulic connectivity of fracture zones encountered (ibid). Leketa (2011) states that “the final result or objective of the tracer test interpretation is usually to determine the rate of flow of groundwater (Darcy velocity) and its flow direction, aquifer porosity and anisotropy, dispersivity, retardation factor and any other physio-chemical characteristics of groundwater”. Other physio-chemical properties to characterise the water that tend to be measured in-situ with portable devices include pH, temperature, salinity, etc.

2.1.5 Digital Elevation Models

In addition to understanding the land use patterns that would potentially impact on the quality of the resource and recharge into the aquifer, Digital Elevation Models (DEM) and remote sensing together with Geographic Information Systems (GIS) data have become increasingly useful in identifying the natural topography that delineates groundwater potential zones (e.g. Vittala et al., 2006; Ganapuram, et al., 2009; Seshadri and Chandrasekhar, 2013). According to Seshadri and Chandrasekhar (2013), this is especially true in areas of extensive urbanisation where use of traditional geophysical survey methods to study changes in topography and geological structures may have constraints in developed areas which are densely populated. This proved to be also true for some of the potential drilling sites in the current study of Johannesburg inner-city, where small tributaries and surface streams are covered with impervious surfaces and flow as subsurface channels.

A DEM digitally represents the topography between points of known elevation and can be used for groundwater resource potential mapping (Liu et al, 2015). According to Liu et al (2015), DEMs can reveal geological features, terrain features and hydrology features, amongst others, which in turn can be related to groundwater potential. The use of DEM data can provide for a relatively quick and inexpensive qualitative methodology for groundwater potential mapping (ibid.). DEM data (Shape) files can also be used as input data in constructing the mesh/ grid of a conceptual model in some of the numerical modelling software.

Thus, there are numerous approaches that could be employed to characterise aquifers and one needs to assess carefully which of these techniques is best suited for a given study and prevailing site conditions. Payne and Woessner (2010) state that after obtaining this data from the different approaches, one can represent both general and unique physical and hydrogeological conditions. Of the above-mentioned approaches and based on available resources, the current study carried a geologic setting assessment, assigning of aquifer parameters based on pumping tests, groundwater chemistry sampling and laboratory testing, and detection of fracture zones for borehole siting using geophysical methods. The DEM maps that were obtained did not provide much information. In the Johannesburg inner-city, there were springs that were once observed (Laburn, 1970), which have since been covered and/ or piped in the process of the changes in the land use and townships development. The knowledge of the former locations of those springs was used to better understand the flow conditions considered in developing the conceptual model.

2.2 Development of conceptual models

A conceptual model is a schematic representation of the groundwater flow system that is conceived. It is drawn into a simplified picture of the best idea of how the aquifer works. The conceptual model is the foundation on which numerical model analysis can be developed (Bredehoeft, 2005; Betancur et al., 2012). It is created with certain assumptions to simplify the field problem. The conventional definition of a groundwater conceptual model is a mostly qualitative and often pictorial description of the groundwater system, including a delineation of the hydrogeological units, the system boundaries, inputs/ outputs, and a description of the soils and rocks and their properties. The first step in modelling is to build a conceptual model of the underlying system. The conceptual model produced informs the modelling approach and the type of modelling software to use (Kumar and Singh, 2015).

A conceptual model design should typically consider nine data sources: geomorphology, geology, geophysics, climate, vegetation, soils, hydrology, hydrochemistry/ geochemistry, and anthropogenic aspects (Kolm, 1996). Once these have been considered, the model should then, at a minimum, include information on boundaries; hydrostratigraphy and hydrogeologic properties; flow directions and sources and sinks; and a field-based estimate of components of the groundwater budget (Anderson et al., 2015; Fernandes et al., 2016). There is, however, complexity in the processes that occur in the natural system and this has largely led to the uncertainties associated with the development of the conceptual models. Amongst others, is the challenge of using the correct Representative Elementary Volume (REV), which speaks to the scale of pore spaces or degrees of fracturing taken into consideration relative to the volume (areal extent) of aquifer under investigation. Nyende et al. (2013) suggest this has led to different approaches that have been adopted in the evaluation of the REV, discussed in more detail in that paper.

The conceptual model is often developed based on assumptions made in an attempt to fill in the gaps in the knowledge of the groundwater system, due to insufficient information available to fully describe the underground conditions. This leads to inherent uncertainties in the conceptualization of the model and thus, the exploration of considerable variations in the interpretation of available data (Krom and Lane, 2012). A general consensus is premised that all models are wrong, but some are useful. Some research studies have investigated the reliability of models and even quantified their uncertainty (e.g. Singh et al., 2009; Bredehoeft, 2005). According to Singh et al. (2010), the different sources of uncertainty in the modelling process can be categorized into: 1) Conceptual uncertainty – which is due to decisions about the conceptual model often made with inadequate knowledge of the underlying subsurface processes and geologic structure that cannot be fully observed; and 2) Parametric uncertainty – where numerous parameters that need to be specified often have to be guessed due to insufficient data or errors in the field data obtained. Bredehoeft (2005), however, argues that “the conceptualization problem does not render models unusable”; it simply introduces uncertainty against which the modeller needs to make a judgement on the appropriateness and adequacy of the conceptual model to represent a given problem.

2.3 Groundwater flow modelling

A groundwater model provides a tool for bringing together, in a simplified representation, the field information, its analysis and a variety of probable ways of how the groundwater system works (Anderson et al., 2015). Models are broadly used to understand groundwater systems and to forecast simulations or recreate past conditions (ibid.). Groundwater simulation models assist in analysing complex real-world problems and issues concerning impacts of groundwater withdrawal and contaminant scenarios. The outputs from models can be used for effective groundwater utilization and management (Cao et al., 2013; Van Camp et al., 2013; Rinaldi et al., 2014; Sahoo and Jha, 2017). In Lagarde et al. (2014), the observed spring attributes were integrated into the conceptual hydrogeologic model to predict the groundwater flow paths through the identified aquifers.

In groundwater model design and development there are often two critical points to consider, which are firstly, the selection of the appropriate software to use and, secondly the correct application of that software product for the specific modelling objectives (Barnett et al., 2012; Kumar and Singh, 2015). In the first instance, the hydrogeological process (flow/ transport) addressed by the model function is identified and thereafter, a simulation framework (domain representation, dimensionality, and solution technique) is chosen, which leads to an appropriate computer software that can meet the demands that are identified. In the second instance, the model spatial extent and discretization, model layers, boundary conditions, and/ or initial conditions, etc. have to be carefully considered to reflect the targeted problem. Kumar and Singh (2015) also state that the modelling objectives will determine the level of the data input, calibration and uncertainty analysis that will be required in the model.

There are three commonly used numerical methods for groundwater flow, which constitute the algorithms that govern the computer model. These are finite-difference (FD), finite volumes (FV) and finite-element (FE) methods (Holzbecher and Sorek, 2005). Generally, in groundwater modelling, FD based software is used most frequently and is followed by FE based software. This is due to the fact FD methods require relatively the least coding efforts.

MODFLOW, a well-documented and popular FD model, "developed by Harbaugh and McDonald (1996) or its modified version has been extensively used for quantifying changes in groundwater flow attributed to recharge, pumping and hydraulic properties of the aquifer" (Zhou and Li, 2011 as cited by Sahoo and Jha, 2017). Although the FE requires the most effort of the three, it is most suitable in representing irregular aquifer geometries encountered in reality (Younger, 2007). Peterson and Western (2014) suggest that although there are various models that exist, calibrating them can be a very challenging task that often leads to oversimplification, which may often jeopardise the predictive performance thereof. However challenging the task maybe, the "models remain a powerful tool for exploring hydrological dynamics such as changes in groundwater pumping" (ibid); and for planning in effective resource management.

It is important to understand the field behaviour and all the assumptions that form the basis of the model in order to avoid applying an otherwise valid model to an inappropriate field situation.

2.4 Groundwater governance

According to modern South African legislation – The National Water Act (NWA) (No 36 of 1998) (Republic of South Africa, 1998), all groundwater is under the overall authority of the national government. Furthermore, the use of all water is subject to the national government's control (represented by Minister of water and sanitation). Thus, all groundwater is public property and the national government is the custodian from which all citizens need to obtain the authorization to use the resource. The national department of water and sanitation is also responsible for keeping a database of all groundwater boreholes around the country as well as keeping track of the general water quality and reserve estimation. The NWA repealed prior legislation that defined groundwater as a local and private resource owned by the owner of the overlying property. However, the implementation and enforcement of the Act is poor (Herrfahrdt-Pähle, 2010). According to the Act, the removal of groundwater from building basements qualifies as water use, as stated in Section 21 (j) – "removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people" (Republic of South Africa, 1998). Therefore carrying this out without the knowledge and authorisation from the national department of water and sanitation constitutes an illegal activity.

The NWA stipulates, in sections 5 to 7, that there should be a development of a National Water Resource Strategy (NWRS), which would bind all authorities and institutions exercising powers or performing duties under the NWA, to properly manage water resources so as to achieve the nation's developmental objectives. The second edition (NWRS2) was published in 2013 (DWA, 2013), following the first edition (NWRS1) that was published in 2004 (DWA, 2004). The Department of Water Affairs (DWA) published a groundwater strategy (DWA, 2010), which stated how much groundwater is reliably available, and where it occurs. The published strategy also sought to create awareness in order to improve knowledge and understanding of groundwater. In addition, the strategy was also used as the main groundwater input to the NWRS2.

The NWRS2 mentions groundwater utilisation as one of the multitude of strategies required to ensure a sustainable water balance, given that surface water yields and water resources infrastructure are fast approaching full utilisation (DWA, 2013). The NWRS2 also promotes "that accessible groundwater should always be utilised … in order to reduce the demand on surface supplies" (ibid.). Interestingly, in the Vaal River Supply System, the water balance system reconciliation strategy targeting year 2030 does not consider groundwater as one of the resources available to supply additional water requirements. The strategy emphasizes implementation of Phase II of the Lesotho Highlands Water Project, which had been scheduled to deliver water to Gauteng by 2020 and has since been re-scheduled to 2026 as things stand, and not subject to further sharp escalation in costs.

At local council level, groundwater governance by the City of Johannesburg has been limited, and monitoring of the usage of groundwater by the public only started from 2017. The lack of governance and monitoring was partly due to inadequate capacity to gather information on the extent of public usage. It was also due to the reluctance to find alternative water sources to create a water supply mix. The city is currently 100% reliant on Rand Water Board for its water supply. The city buys the bulk potable water from Rand Water through its municipal owned entity, Johannesburg Water, whose main function is to then distribute this water to the city's residents. The ongoing threat of water shortages and the recent drought of 2016 has since elevated the subject of long-term water security. Since 2018, the city has incorporated the usage and governance of groundwater resources, amongst others, in the currently drafted Water Services Bylaws. In 2016, the city also initiated a project (of which this study is a work package therein) of trying to map the groundwater resources across the city's borders with the ultimate aim of developing resource extraction boreholes, a monitoring network and a Groundwater Management Plan for the City of Johannesburg.

3. RESEARCH METHODOLOGY AND MATERIALS

3.1 Desktop Study

A desktop study was conducted which focused on identifying any work done on hydrogeological investigations within the Johannesburg inner-city. Further desktop research focused on a comparison of methods in the modelling of groundwater quantity estimation. In addition, desktop research was used to explore further the current knowledge of the specific geology of the Johannesburg inner-city. The city's geotechnical data bank was used to consult literature related to geotechnical investigations that were done for different construction sites within the inner-city, and information was extracted on the depth of the different geological formations.

The work of De Beers (1965) was mainly relied on for site specific geological information. Additional information was obtained from geotechnical reports and GIS data to construct the aquifer boundaries in order to generate the conceptual model. Further literature search and consultations were carried out to verify and validate any site specific hydrogeological features and the lateral extent of the aquifer.

3.2 Survey Questionnaire

A survey was conducted using a questionnaire that was sent out to the property managers and owners of commercial buildings in the inner-city in order to assess which buildings were experiencing groundwater seepage. The survey questionnaire sample is attached as ***Appendix A***. The information from the questionnaires returned was collated and used to delineate the spots that indicate the availability of groundwater across the inner-city, and to identify any likely high groundwater potential zones. This survey information was also used in the planning of site visits and borehole siting.

Verification was done by visiting the building basements from the respondents and making observations on the type of seepage affecting the building, the condition of infrastructure services in and around the building as well as checking the chemistry of the water that is seeping into the basements, and measuring the heights of the basements. Water table levels were estimated using the height of the basements and water markings on the walls. Observations made in the building basements were then contrasted with aquifer thicknesses obtained from available literature.

3.3 Field work

The CoJ appointed the Council for Geoscience to carry out the drilling component of field investigation on its behalf. The borehole construction design was based on the standard specifications prescribed by the Council for Geoscience. With regard to the drilling specifications, standard rotary air percussion drilling technique was used. Borehole depths were expected to reach a maximum depth of 80m if soil conditions permitted. Drill core samples were collected and logged at every meter interval and used to determine the specific lithology of the borehole and reasonably extrapolated to surrounding areas.

The critical focus and terms of reference of the project were set up as follows:

I. Confirmation of site specific geology, identification of springs and collection of data required to design a conceptual model – this activity contributes to addressing Research Questions 1 and 2.

II. Determination of water levels across the Johannesburg inner-city – this activity contributes to addressing Research Questions 1 and 3.

III. Determination of the rate of water seepage within the Johannesburg inner-city – this activity contributes to addressing Research Questions 1 and 2.

IV. Borehole development and data collection – this activity contributes to addressing Research Questions 1 and 3.

V. Borehole testing (quantity and quality), by pumping test and laboratory chemical tests – this activity contributes to addressing Research Questions 1, 2 and 3.

3.4 Development of a conceptual model

A conceptual hydrogeological model representative of the aquifer(s) within the inner-city was developed using the detailed geological map and other parameters determined from the field work mentioned above. Several assumptions were made, such as the generalized flow circulation depth observed by Abiye (2011) for the greater Johannesburg area, in order to simplify the model. Water table levels data and geologic profiles depths were also collected by examining studies of numerous geotechnical reports available in the City's Geo-data Bank. This was meant to minimize uncertainties of the model. The detailed lithology from the geotechnical data coupled with simplifying assumptions, provided the requirements for the conceptual model that served as input into the numerical model.

3.5 Development of a numerical model

A numerical groundwater model representative of the aquifer was developed using SPRINGfree 4.32 Software (König et al., 2017), which is based on the FE method, and it is capable of predicting the long term annual sustainable abstraction rate that will allow for the required permanent drawdown of the water table. The purpose of this model is to simulate (and to predict) the groundwater system response to withdrawal in the form of depression of groundwater levels. This contributes to addressing Research Questions 1, 2 and 3.

3.6 Use options of the abstracted groundwater

Remedial actions to control groundwater seepage are proposed in terms of pumping regime and sustainable abstraction rates. Several uses of the groundwater resource are explored with possible implementation scenarios determined by the quality and infrastructural requirements. Based on the findings of the analysis, suitable water uses are recommended, taking into account the quantity and quality of the water. Cost of implementation and regulation mechanisms were explored. This addresses Research Question 3 of the study.

The results of the field pumping tests were used to determine hydraulic conductivities and the measuring of static water levels was used to establish the recharge rates respectively in the Johannesburg inner-city area. These two parameters together with the depth to solid rock (aquifer thickness) were then entered into the numerical model to establish how much groundwater is available within the area. Different consumption scenarios were assumed to find out if the water is available in sufficient quantities that make it worthwhile to abstract as a realistic proportion of the demand (i.e. as a complementary resource of the municipal supply) for the Johannesburg inner-city. A scenario analysis is also carried out to evaluate the best use for the water based on inner-city requirements and conditions. Lastly, consultations with the Department of Water and Sanitation were carried out to obtain clear guidelines as to whether the city can extract and sell groundwater to residents in order to recoup the associated running costs if infrastructure would be developed around this resource.

4. RESULTS

4.1 Desktop Study

4.1.1 Regional Geology of Greater Johannesburg Area

According to geological maps produced by the Council for Geosciences, the regional geology surrounding the study area comprises various Supergroups and Groups, viz. the Basement Complex, Johannesburg Dome of the Central Kaapvaal Craton, West and Central Rand Group of the Witwatersrand Supergroup, Klipriviersburg Group of the Ventersdorp Supergroup, Black Reef Formation, Chuniespoort and Pretoria Group of the Transvaal Supergroup, Vaalian Syenite, Post Transvaal Diabase, Dwyka and Ecca Group of the Karoo Supergroup. ***Figure 2*** shows the regional distribution of the geology across the greater Johannesburg area, with the red dot in the map indicating the Johannesburg inner-city (study area).

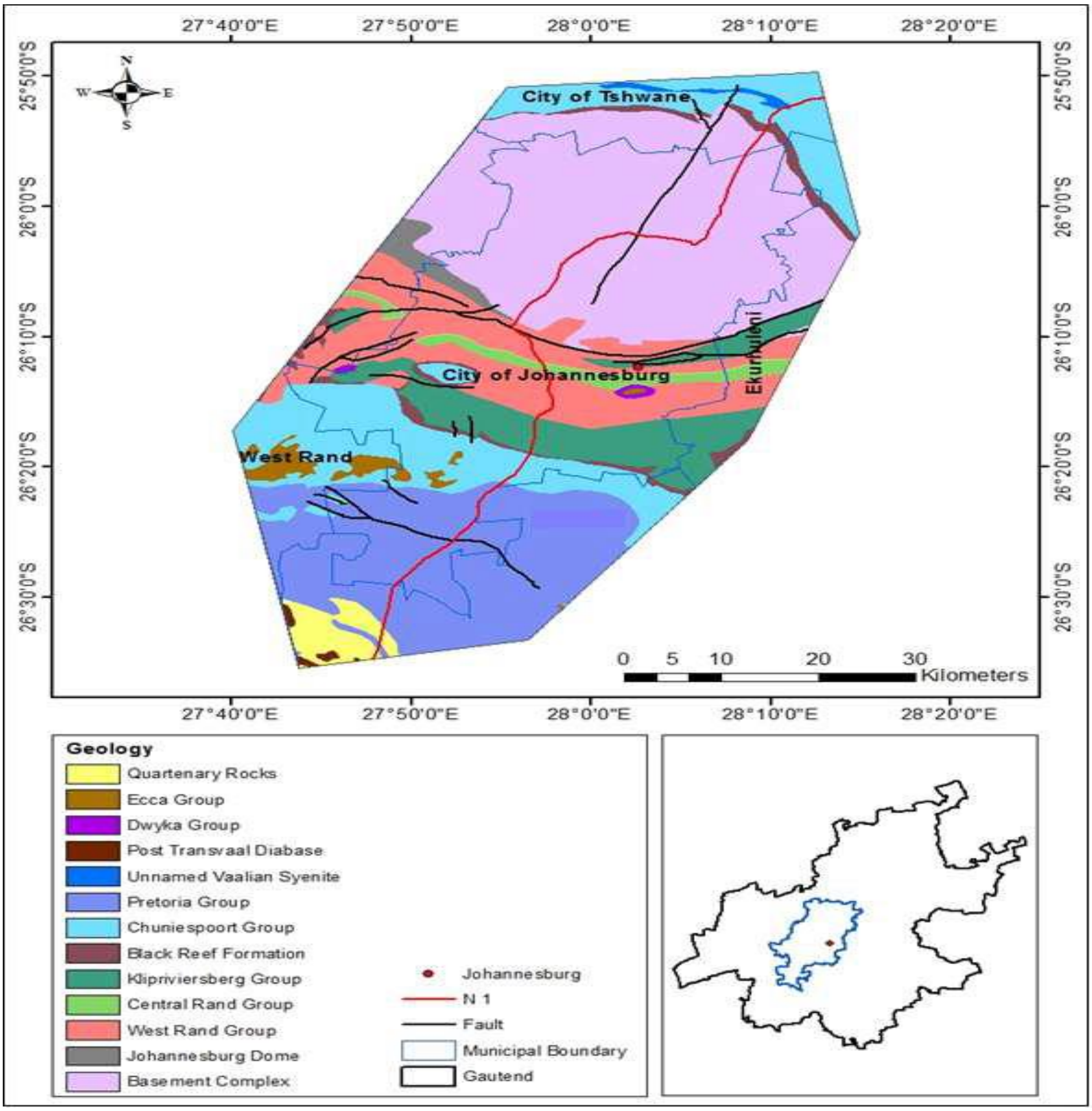

Figure 2: Regional geology of the greater Johannesburg area (Source: Council for Geoscience, 2017)

Groundwater occurrence is determined by the specific lithology and structure that is found on site. The typical formations and lithological distribution of the rocks found within the regional Supergroups across the greater Johannesburg is shown in ***Table 1***. The study area is located within the West Rand Group of the Witwatersrand Supergroup which has been intruded by the Klipriviersberg Group of the Ventersdorp Supergroup.

Table 1: Typical geological formations and lithology across the City of Johannesburg (Source: Council for Geoscience, 2017)

Chrono Stratigraphy	Basin	Supergroup	Group	Subgroup	Formation	Lithology/ Geology
Palaeozoic Erathem	Karoo	Karoo	Ecca		Vryheid	Diamictite (polymictic clasts, set in a poorly sorted, fine-grained matrix) with varved shale, mudstone with dropstones and fluvioglacial gravel common in the north
			Dywka			Diamictite (polymictic clasts, set in a poorly sorted, fine-grained matrix) with varved shale, mudstone with dropstones and fluvioglacial gravel common in the north
Mokolian Erathem			Post Transvaal Diabase			Dolerite
Vaalian Erathem	Transvaal	Transvaal	Chuniespoort	Malmani	Monter Cristo	Stromatolitic dolomite with abundant chert
					Black Reef	Quartzite, subordinate conglomerate and shale
Randian Erathem		Ventersdorp	Platberg			Conglomerate; volcanic felsite; quartz porphyry; subordinate amygdaloidal lava; subordinate porphyritic lava
			Klipriviersberg		Loraine	Amagdaloidal, basaltic/andesitic lavas and tuffs
					Alberton	Basaltic lava (porphyritic), tuff (amygdaloidal in places)
					Westonaria	Basalt, tuff
					Venterspost	Conglomerate, quartzite
	Witwatersrand	Witwatersrand	Central Rand	Turffontein	Mondeor	Conglomerate, quartzite
					Elsburg	Quartzite, minor/subordinate conglomerate
					Kimberly	Quartzite, conglomerate
				Johannesburg	Booysens	Shale, subordinate quartzite
			West Rand	Jeppestown		Shale, quartzite, subordinate lava, minor conglomerate
				Government		Quartzite, shale, minor/subordinate conglomerate
				Hospital Hill	Brixton	Quartzite, shale
					Parktown	Shale, thin quartzites
					Orange Grove	Fine- to medium-grained quartzite, shale (in middle of formation)
Swazian Erathem	Linden Gneiss (Archean basement)					Hornblende and/or biotite tonalite gneiss

4.1.2 Locality Map and Specific Site Geology

The boundaries of the 'inner-city' as defined in this research were determined by the reported sites of groundwater seepage in basements. The desktop study conducted indicated that a significant amount of work had earlier been carried out by De Beer (1965), which provided some knowledge about the geology of the Johannesburg inner-city. ***Figure 3*** shows the locality of the sites together with the expected underlying lithology. The general lithology map is obtained from Geographic Information System (GIS) data. The inner-city is located on a ridge that forms a watershed divide between the greater Limpopo and Vaal River Systems situated on south west – north east direction along the Braamfontein – Hillbrow – Yeoville suburbs. The area of investigation is also generally located along the graben valley formed by faulting along the contact between the Ventersdorp Supergroup lavas and the Witwatersrand quartzites and shales.

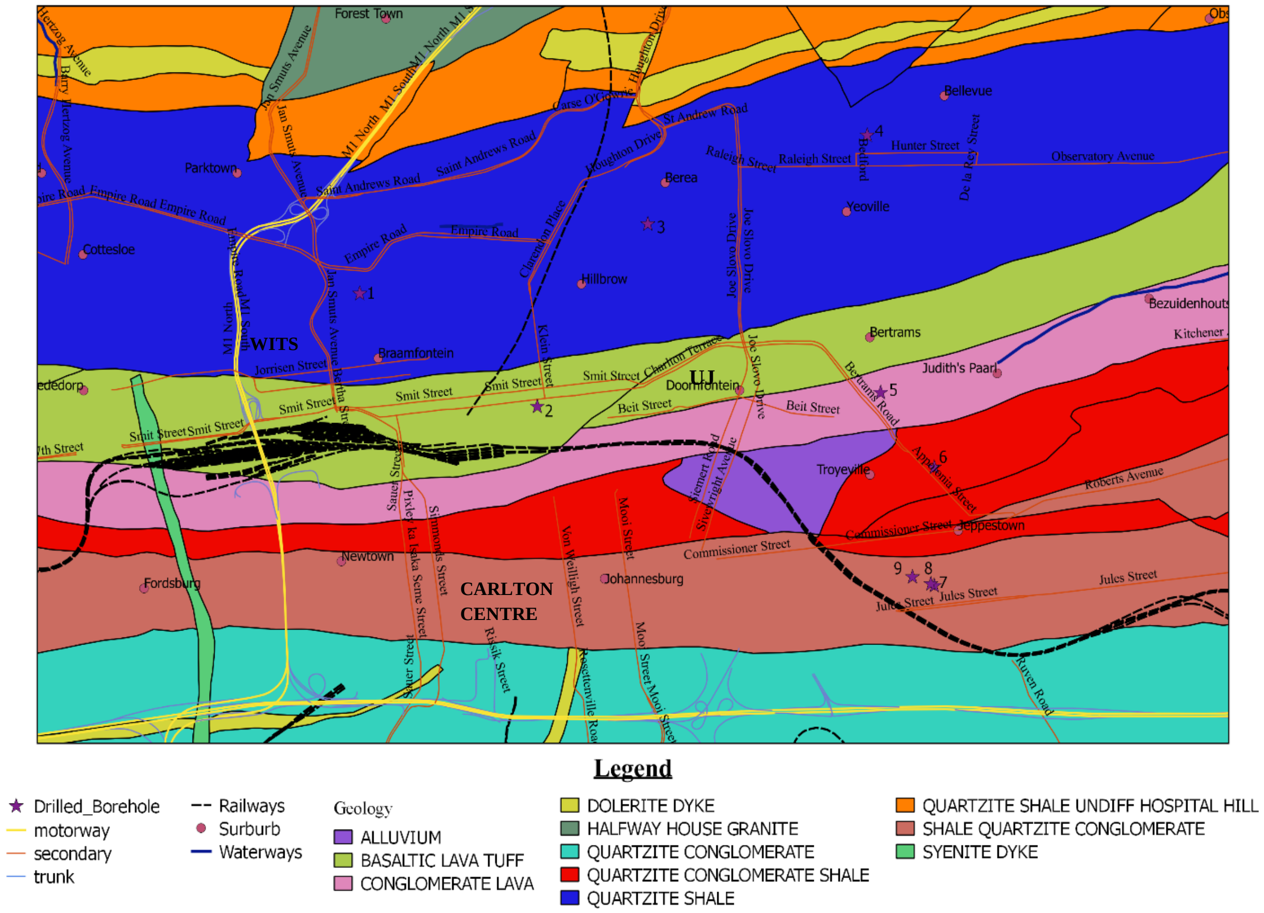

Figure 3: Locality map of the study area showing drilled borehole sites and general underlying lithology

The location of each of the nine (9) borehole sites shown on the map is presented in ***Table 2.*** The sites selection was determined by availability of open green space in the area that is large enough to be able to use significant quantities of groundwater, has adequate access for the drill rig and sufficient security so as to not expose the borehole equipment to vandalism when operational.

Table 2: Drilled borehole sites

No.	**Borehole Site**	**Suburb**	**Longitude**	**Latitude**
1.	Helpmekaar Kollege	Braamfontein	28.0351	-26.1886
2.	The Green House	Hillbrow	28.0457	-26.1951
3.	Barnato Park High School	Hillbrow/ Berea	28.0523	-26.1846
4.	Yeoville Boys Primary School	Yeoville	28.0654	-26.1795
5.	Betrams Skills Centre	Betrams	28.0662	-26.1943
6.	Troyeville Primary School	Troyeville	28.0694	-26.1986
7.	John Mitchell Primary School	Jeppestown	28.0694	-26.2054
8.	Jules High School	Jeppestown	28.0692	-26.2053
9.	Bertha Solomon Rec Centre	Jeppestown	28.0681	-26.2049

4.1.3 Hydrogeological Characterisation of the Greater Johannesburg Area

Much work has been published about the general hydrogeological characterisation and historical water supply overview of the greater Johannesburg area (Barnard, 2000; Abiye, 2011; Dippenaar, 2015). These publications generally cover all the four types of aquifers found in the greater Johannesburg area with their estimated yield ranges (***Figure 4***). There is however lack of available groundwater monitoring data in the inner-city. Borehole information obtained from the Department of Water and Sanitation (DWS) database has geographical distribution of the boreholes that is skewed and incomplete. Faulting occurs between the contacts of the Ventersdorp lavas and the quartzites and shales of the Johannesburg graben valley. High volumes of groundwater are associated with these structural features and these high expected yields have not been quantified.

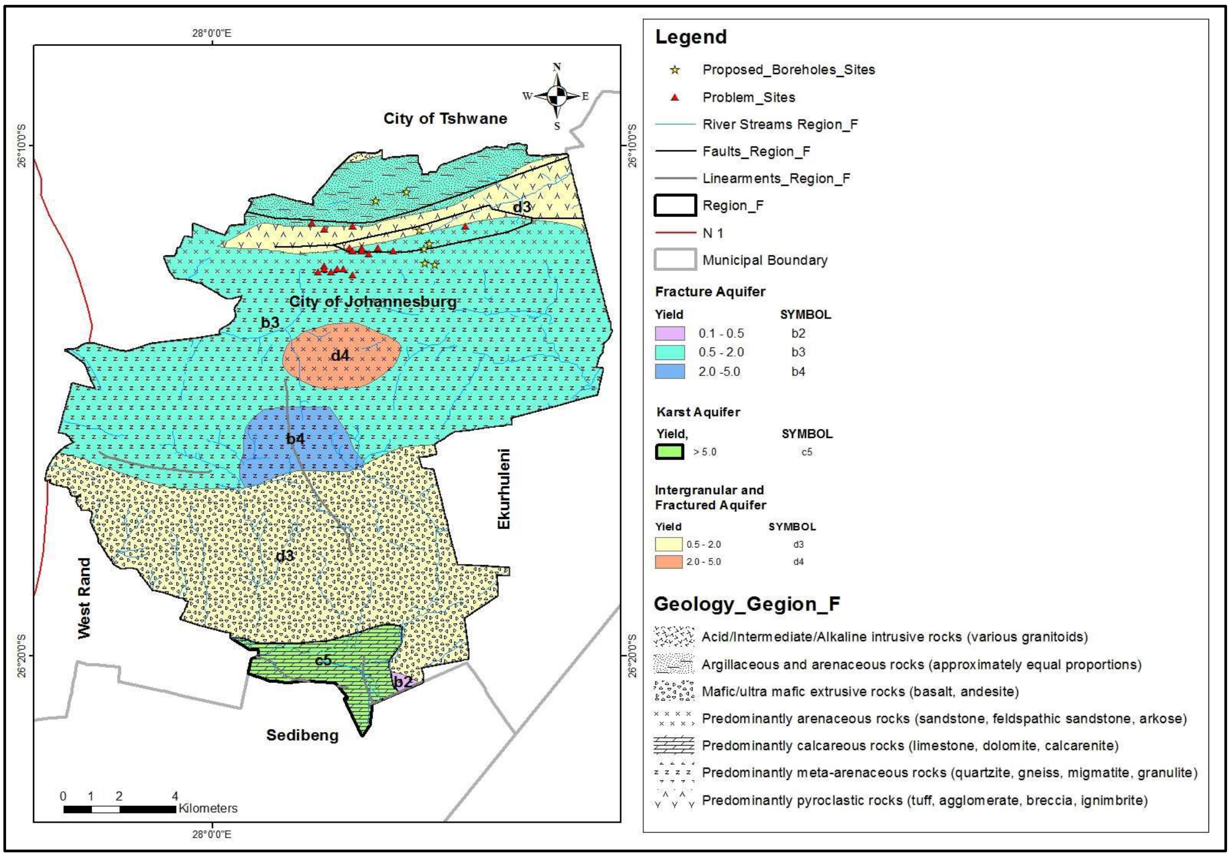

Figure 4: Hydrogeological setting of Johannesburg (yields in litres per second), after Barnard (2000)

The dolomitic karst aquifers, which have the highest yields have received the most attention in sourced literature (Schröder et al., 2006; Pietersen et al., 2011; Leketa et al., 2018). Research also presented the general recharge dynamics, possible groundwater flow direction, the dominant groundwater circulation depth and the human impact of pollution within the Gauteng City Region as a whole. These studies have contributed significantly to the understanding of the groundwater potential of the greater Johannesburg region. Barnard (2000) classified the fractured rock aquifers and intergranular fractured aquifers found in the study area as generally minor aquifers with borehole yields of less than two litres per second. The effect of faulting on groundwater availability in the study area is not exactly known and thus needs to be investigated in more detail. From historical texts (e.g. Laburn, 1970), it is gathered that water supply in the early days of the founding of Johannesburg initially depended on springs that were located within the study area.

The available texts, however, fall short in addressing site specific characterisation of the aquifer(s) in the Johannesburg inner-city and, more importantly, do not estimate available groundwater quantities in the area of interest. Several modelling studies have been conducted in South Africa (e.g. Seyler et al., undated; SRK Consulting, 2016) but none has focused on the Johannesburg area and more specifically on the Johannesburg inner-city. This is because a large urban population is largely dependent on bulk surface water supply as the more easily accessible and 'reliable' water source.

4.2 Survey Questionnaire Analysis (Water levels within the inner-city)

A network database consisting of commercial property owners and managers was used to circulate the questionnaire electronically as wide as possible within inner-city residents. There were 59 properties that returned filled-in survey questionnaire documents (***APPENDIX A***). Due to time constraints in the project and availability of property managers, 30 buildings were visited and observations made are as shown in ***APPENDIX B***. The sample of the buildings visited was representative enough, because it covered all the suburbs in the inner city and also covered a wide range of types of buildings.

From the visited basements (Tabulated list in ***APPENDIX B***), the average basement depth was measured and calculated to be about 8 meters below ground level (mbgl). The shallowest basement depth observed was 3m below ground level and the deepest was 18m. These depths were calculated by counting the number of basement levels available, then taking the height of the basement (with the slab thickness also taken into account), and multiplying the two. Forty percent (40%) of the basements in the sample are less than 6m deep and all the others are 6m deep or more. The mode of the sample is 6m, meaning, two basement levels were encountered most frequent (20%). Forty percent (40%) of the basements had three basement levels or more.

The water table level around the basements was estimated by observing and noting the damage and seepage on the walls. This is not very accurate as other walls had been repaired and thoroughly sealed. Some building managers assisted with the seepage history thereof. The average water table level observed ranged from 2.5 mbgl on the far West part of the study area to 14 mbgl on the Central part to the Eastern part, with an overall average water table level of 7 mbgl. This is consistent with the seepage trend observed, as the basements which had consistent groundwater seepage had three basement levels (±9m deep) or more. Some of the ones with two basement levels were reported to have occasional seepage occurrence, making at least 60% of the basements in the inner city to undergo occasional to regular flooding. Thus on average, the estimated pumpage required in order to avoid groundwater seepage into most of the basements would need to result in over 1m depression of the water table. The occasional flooding would be completely eliminated in the two levels basements, and reduced or eliminated in the three levels basements.

4.3 Field Work

4.3.1 Borehole development and testing

The Council for Geoscience (CGS) was appointed as a service provider to implement the borehole development and testing programme for CoJ. This field work was carried out between September and November 2017. Borehole development was done in order to establish the specific in-situ geology of the study area. The following summary of results were obtained from this work (Data source: Council for Geoscience, 2017). It can be seen from the profiles, ***Figures 5 – 13***, that there are three (3) main aquifers identifiable in the study area viz. the confined Slate, the confined Dolerite and the unconfined Quartzite. The water strike in the boreholes was encountered at an average of 39m below ground surface.

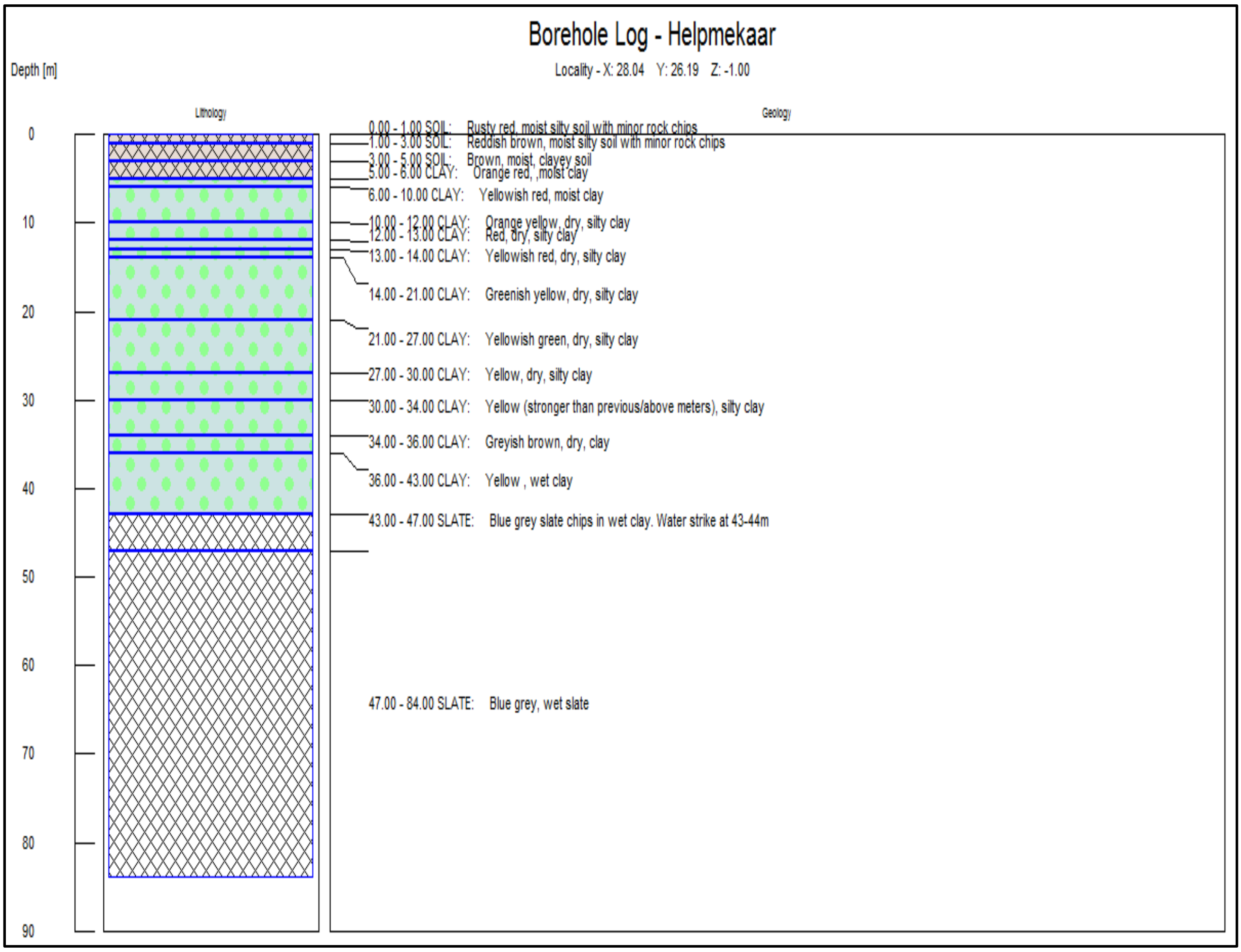

Figure 5: Borehole log profile of Helpmekaar School (Data source: Council for Geoscience, 2017)

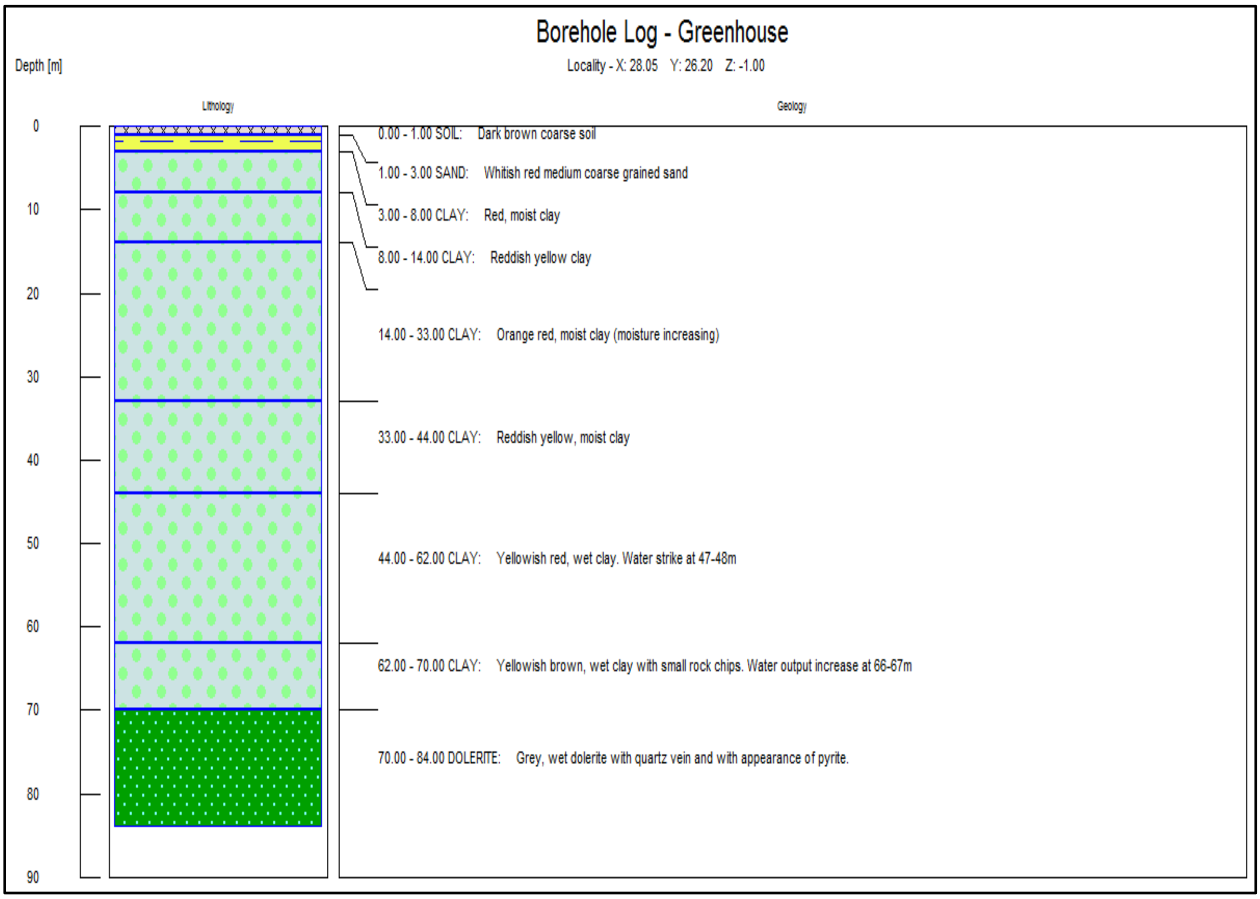

Figure 6: Borehole log profile of Greenhouse centre (Data source: Council for Geoscience, 2017)

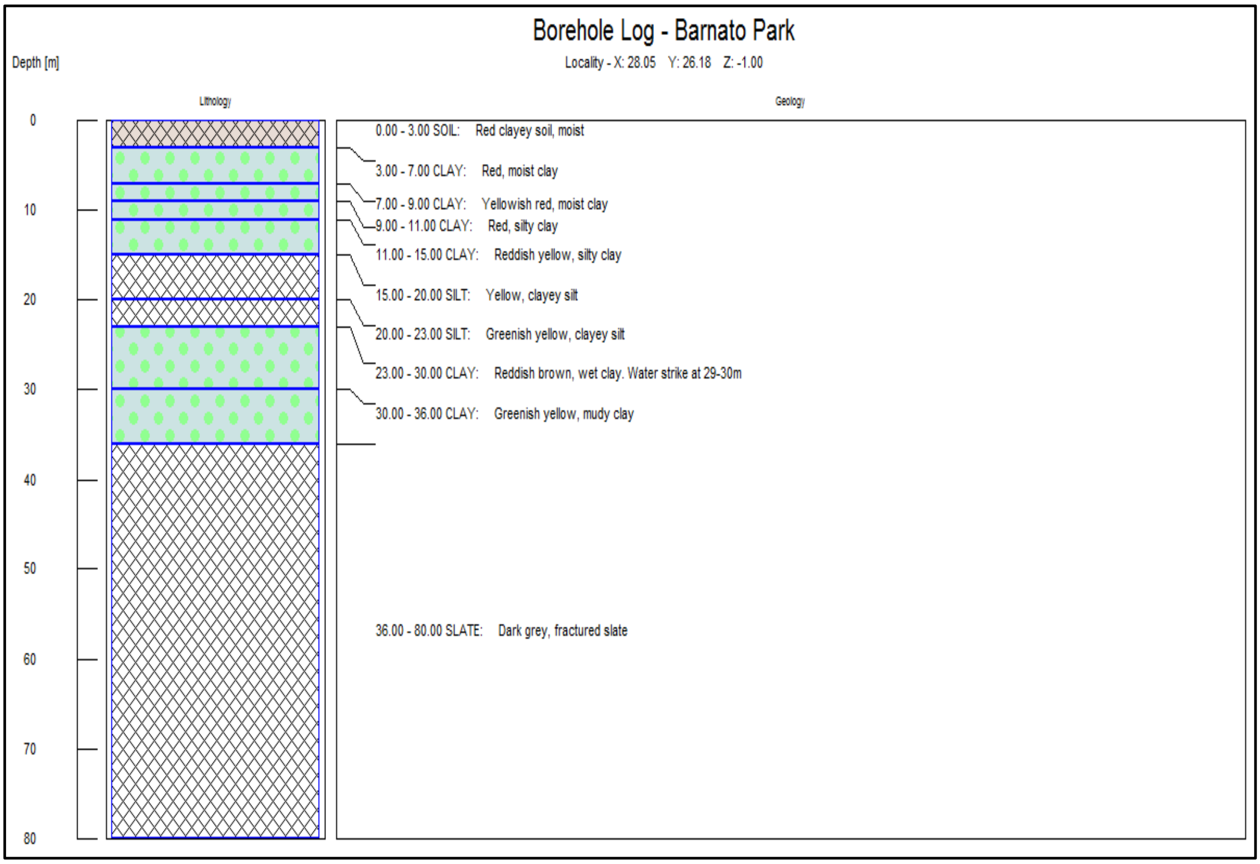

Figure 7: Borehole log profile of Barnato Park High School (Data source: Council for Geoscience, 2017)

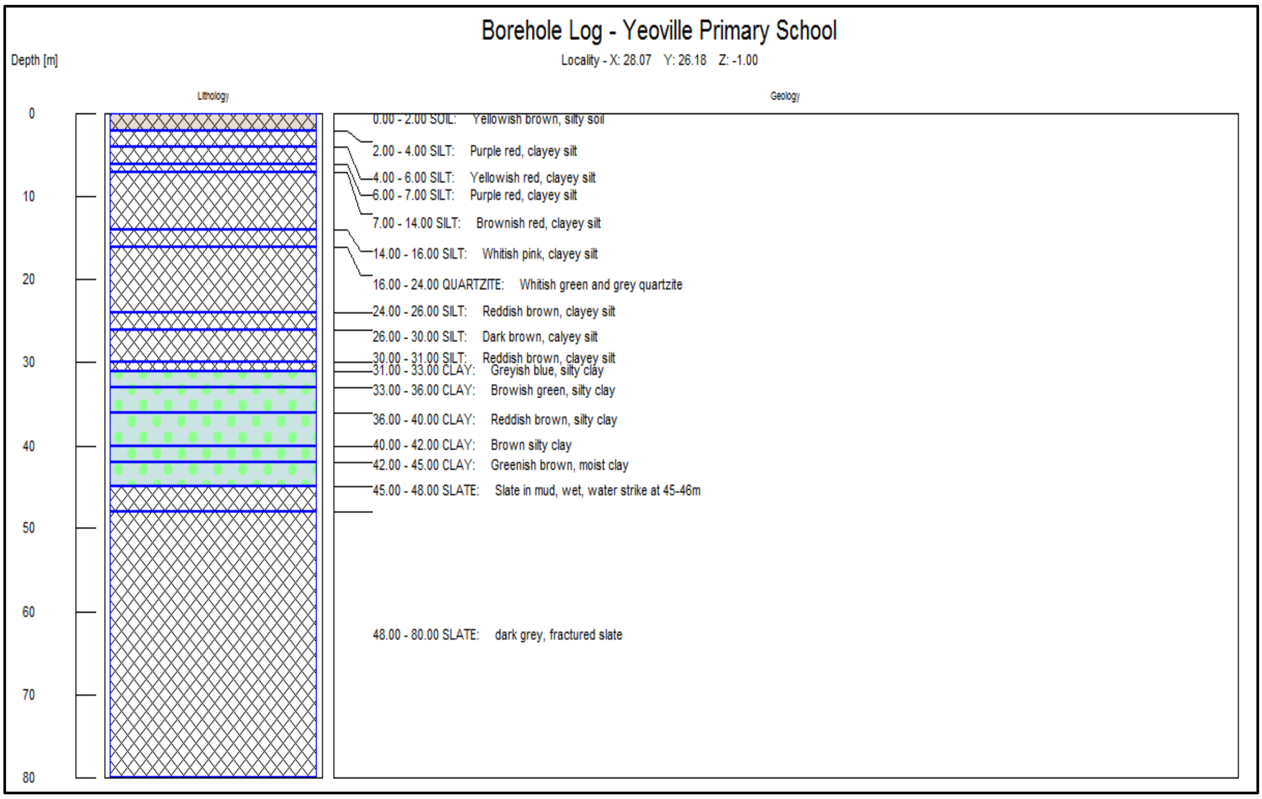

Figure 8: Borehole log profile of Yeoville Primary School (Data source: Council for Geoscience, 2017)

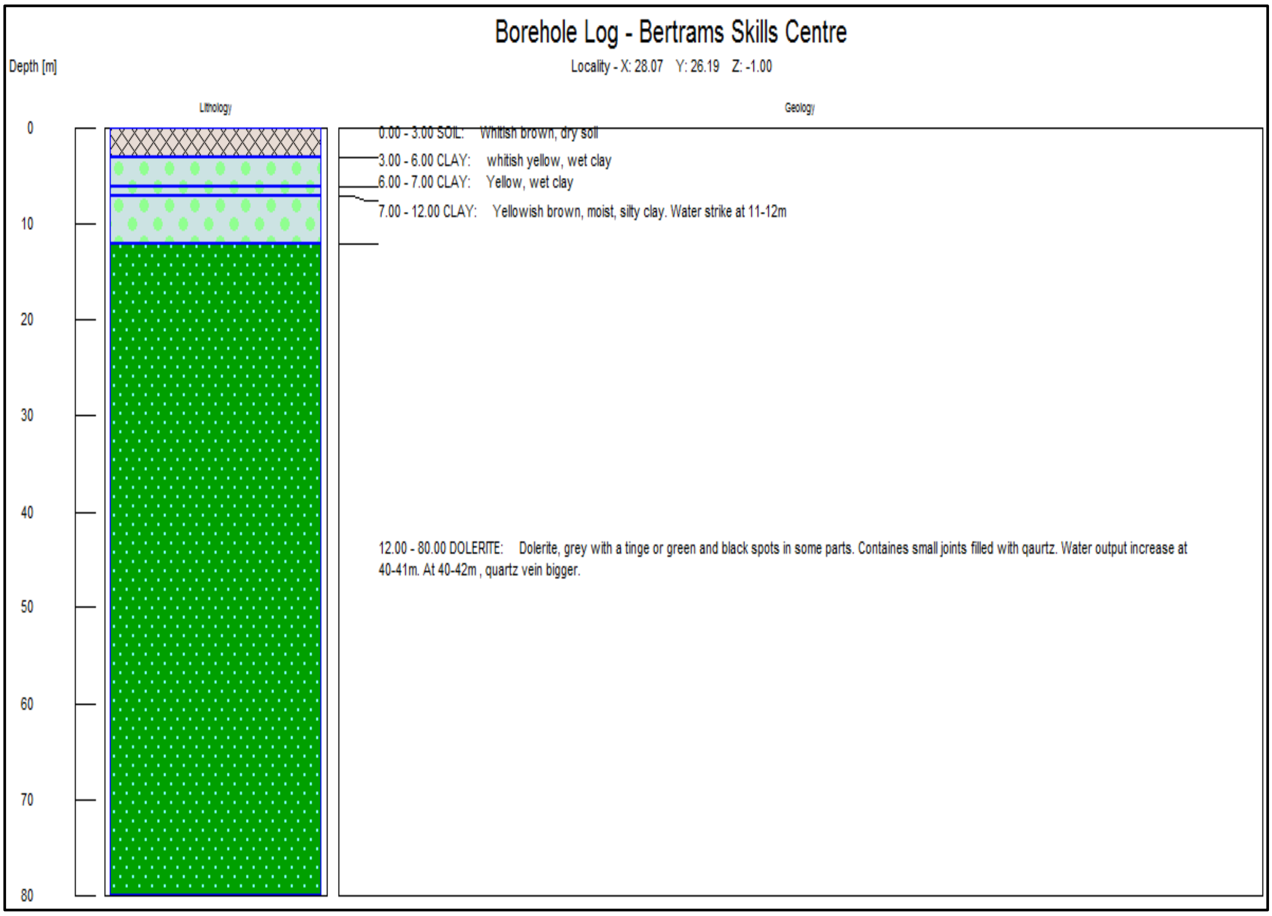

Figure 9: Borehole log profile of Betrams Skills Centre (Data source: Council for Geoscience, 2017)

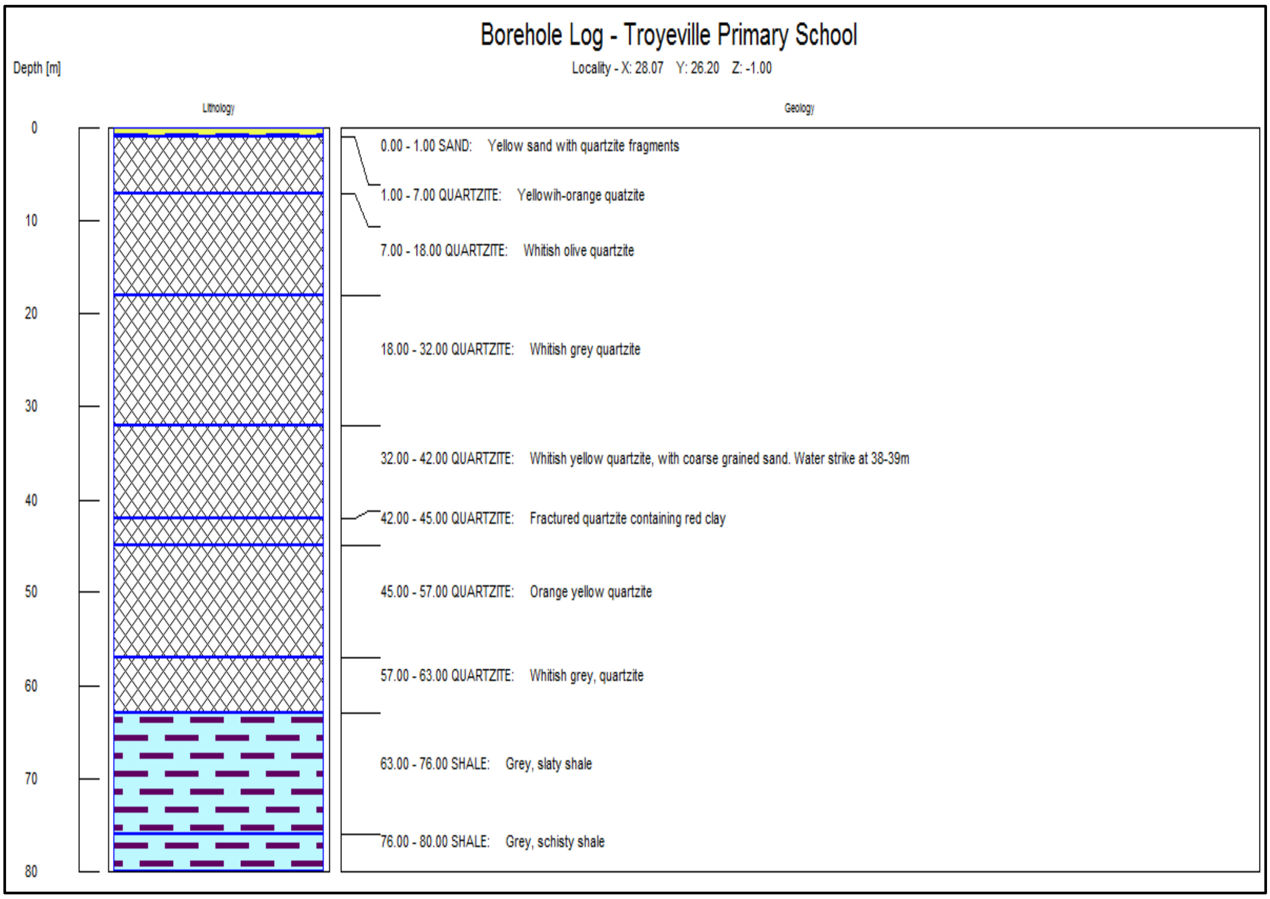

Figure 10: Borehole log profile of Troyeville Primary School (Data source: Council for Geoscience, 2017))

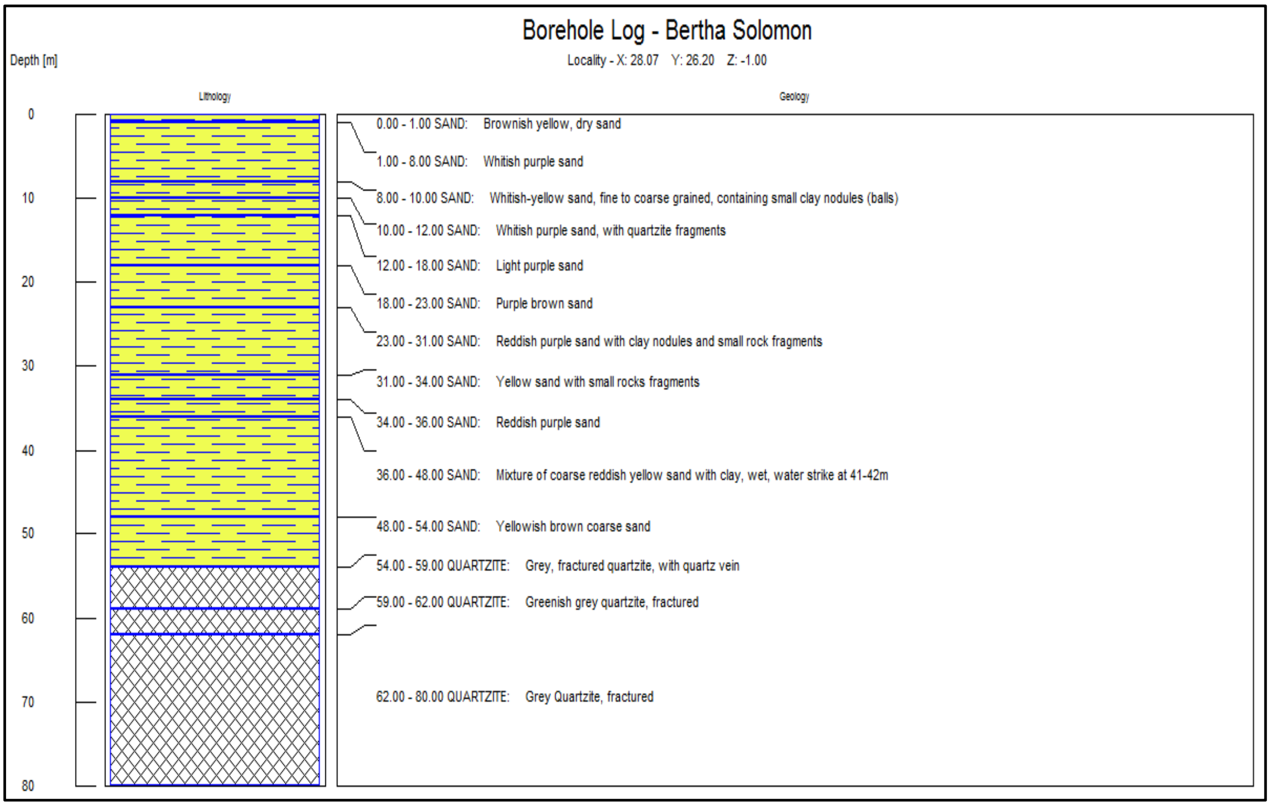

Figure 11: Borehole log profile of Bertha Solomon Recreational Centre (Data source: Council for Geoscience, 2017)

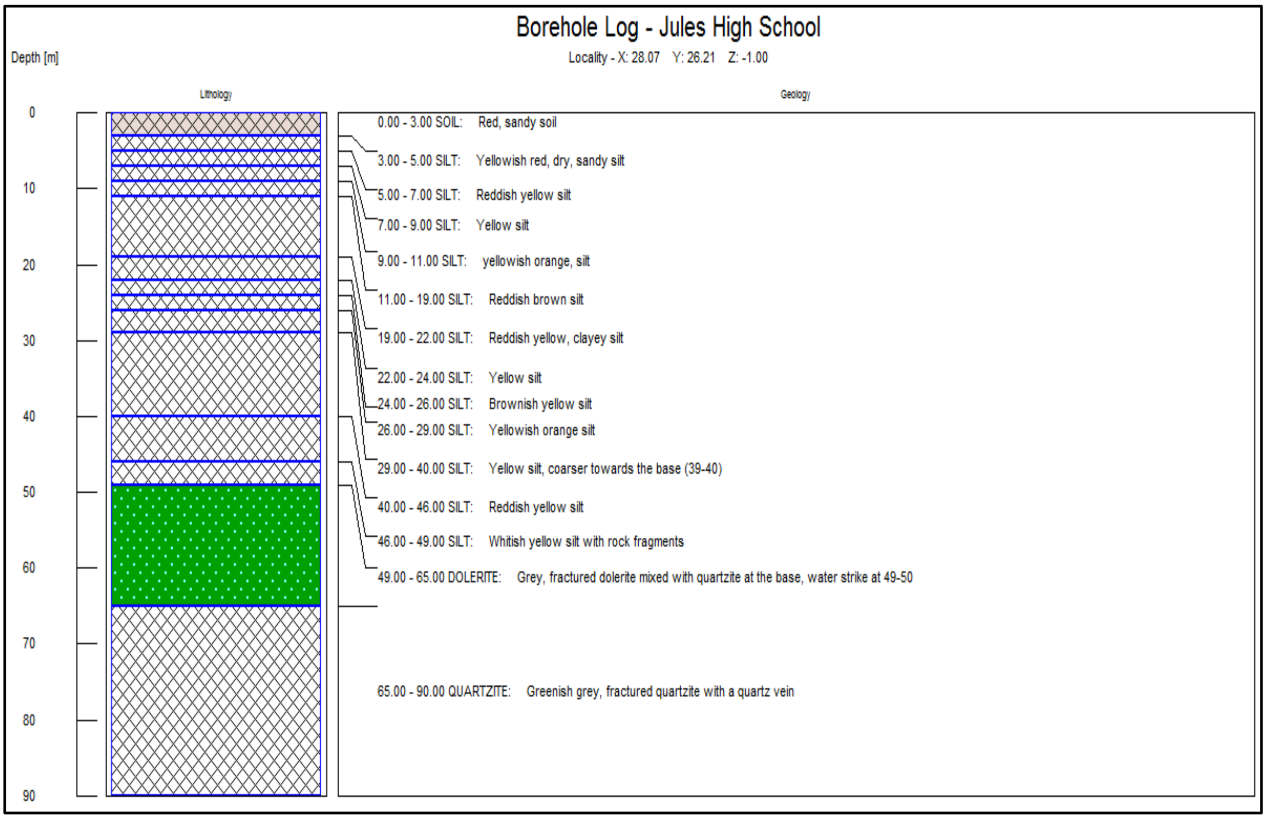

Figure 12: Borehole log profile of Jules High School (Data source: Council for Geoscience, 2017)

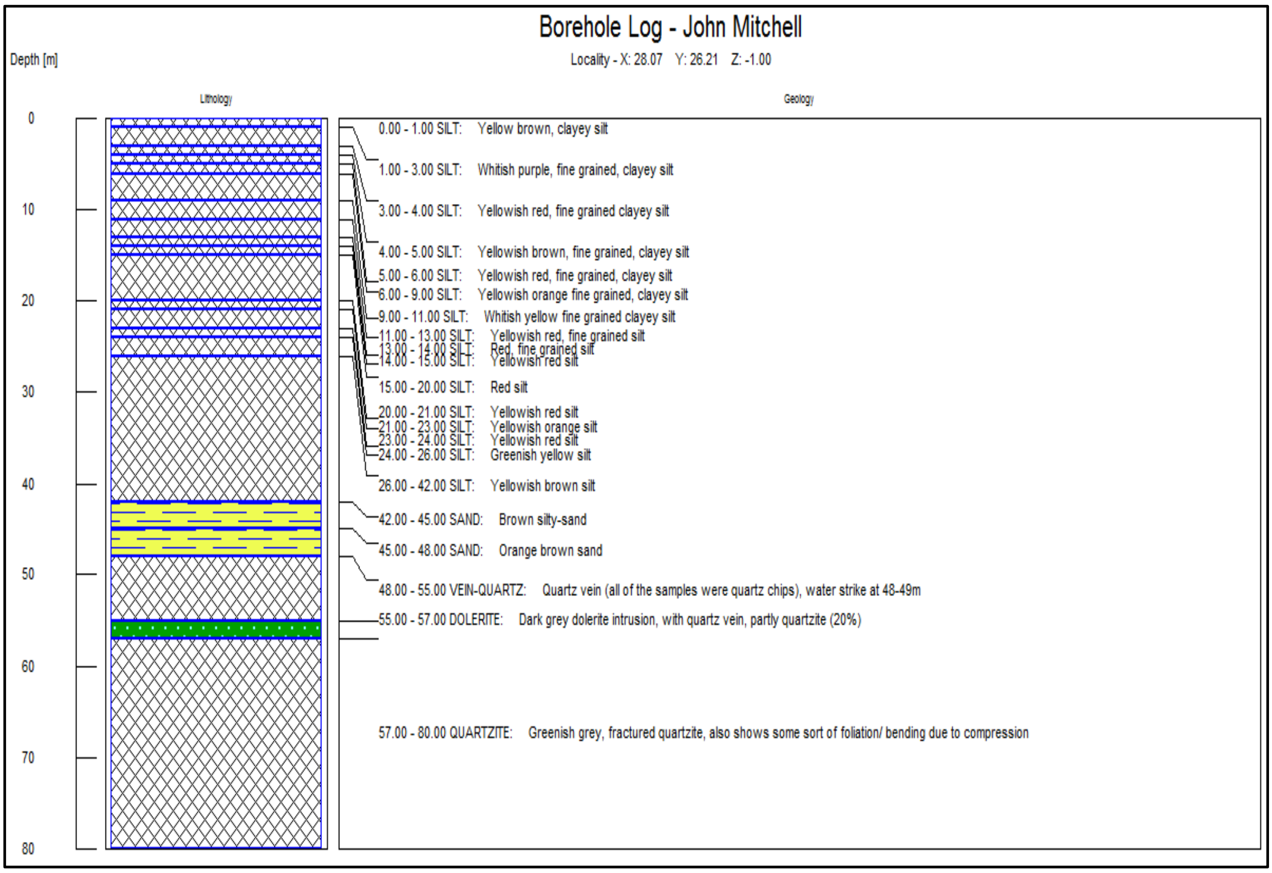

Figure 13: Borehole log profile of John Mitchell Primary School (Data source: Council for Geoscience, 2017)

4.3.2 Chemistry/ quality analysis

Water sampling was possible at eight of the thirty basement sites that were visited. Firstly, samples were taken for chemical analysis in order to verify whether the source of the water seeping into the basements was municipal supply leakages or groundwater. Secondly, the chemistry results were used to identify and categorize the groundwater at the different locations, including the drilled boreholes, in order to possibly trace flow paths and aquifer interconnectedness. This was done by employing STIFF diagrams which are used to indicate the groundwater's element enrichment that can be ascribed to the interaction of the traversing groundwater with the different rock types. The element enrichment is indicated by the peaks in the diagrams, which represent milliequivalence per kilogram (meq/kg). ***Figure 14*** shows the results of all the sampled locations (basements and boreholes) that were obtained.

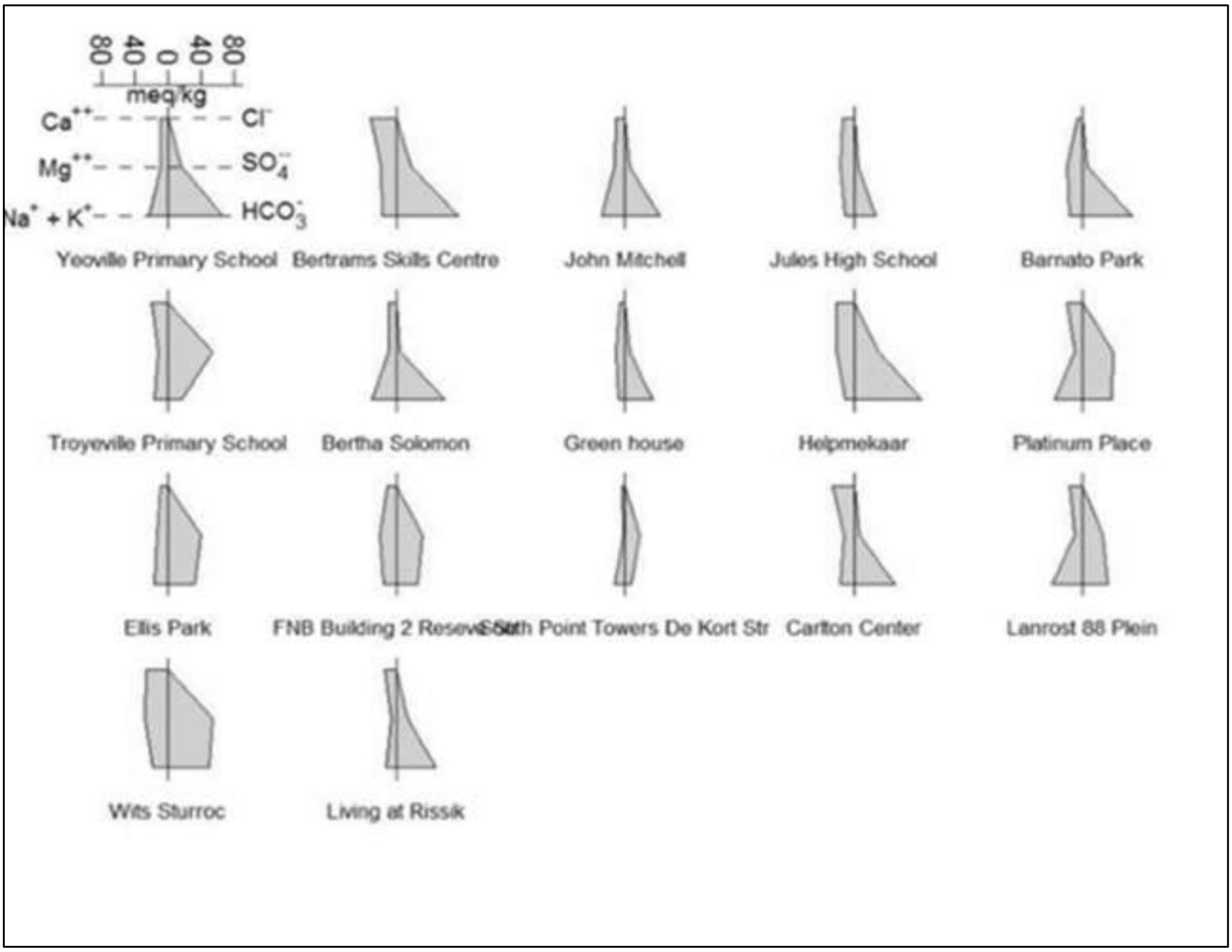

Figure 14: Schematic representation of elements enrichment in water samples using STIFF Diagrams (Source: Council for Geoscience, 2017)

From the above STIFF diagrams, it can be seen that groundwater from Yeoville, John Mitchell and Bertha Solomon show similar peaks in magnesium (Mg), sodium (Na) and alkalinity or bicarbonate (HCO3). The similar enrichment in John Mitchell and Bertha Solomon could be due to the fact that they are in close proximity, have a similar geology and are probably in the same aquifer (CGS, 2017). The STIFF diagrams for Betrams and Helpmekaar show a similar shape with respect to peaks in magnesium, sulphate (SO4) and alkalinity, although Betrams also shows slightly higher calcium (Ca) values. The elements indicate hardness in the water which is mainly present in many sedimentary rocks, indicating that the recharge source of this water is outside the boundary of the study area. Betrams also shows some similarities to Troyeville in calcium and magnesium enrichment, but Troyeville shows higher levels of sulphate enrichment, which could be associated with anthropogenic activities (ibid).

Tested against the SANS 241-1:2015 standard limits, the water at Yeoville Primary was the only one that did not comply in full. The non-compliance relates to the high levels of manganese and iron that could both lead to chronic health problems. A closer look into the available geological maps (De Beer, 1965) shows that there is an iron bed that runs west-easterly in the quartzite shale formation of the Hospital Hill subgroup. The high iron content could also be due to rusting steel casings and thus, further tests will be required once pumpage operations of the borehole have commenced.

Jules High, Barnato Park and Green house show a similar shape with respect to peaks in magnesium and alkalinity. Ellis Park, FNB Building (2 Reserve road) and Wits Sturroc show similar peaks in sulphate and magnesium, which could be an indication that they are receiving water from the same source (CGS, 2017) and are within the same aquifer with the water flowing along a relatively straight line in the East to West direction (from Wits Sturroc, through FNB building and surfacing at Ellis Park). The water at Ellis Park appears at ground level as seeping groundwater.

Platinum Place and Landrost 88 Plein show similar peaks in sodium, sulphate and alkalinity which is consistent with the fact that they are in relatively close proximity and thus, may have the same geology and probably are in the same aquifer. The same observation can be made with Carlton Center and Living at Rissik as the two show similar peaks in calcium and bicarbonate, which could be indicative of enrichment from the same source. South Point towers, which is on corner De Korte and Station streets in Braamfontein, does not show any similarity to any of the other sites and does not show any strong peaks in any of the ions, which could be an indication of neutralised water and hence municipal supply water seeping in from surrounding leaking infrastructure.

4.4 Development of Conceptual Hydrogeological Model

The conceptual model developed here was based on data obtained from geological maps and the results of the above-mentioned hydrogeological study carried out by the Council for Geosciences, commissioned by the CoJ.

The objective of the modelling exercise was to:

i. Estimate the quantity of water available
ii. Confirm the ground water levels in the area and verify the current status quo of flooding in the basements
iii. Determine the quantity of water to idealistically withdraw in order to obtain an average decline in overall ground water levels, i.e. groundwater system response to withdrawal.

The conceptual model developed gives a picture of the site specific characteristics of the aquifers underlying the Johannesburg inner city area. The main focus of the simplified conceptual model is to delineate the hydrogeologic units and set system boundaries. The hydrochemical cycle is ignored in this paper and the reader is referred to studies by Abiye (2011) for more insight on this topic.

According to the general study of Barnard (2000), there are two main aquifer classifications in this area characterised in terms of porosity. They are the fractured aquifer and the intergranular and fractured in aquifer with yield range of 0.5 – 2.0 l/s. Abiye (2011) notes that groundwater circulation in the Johannesburg area is generally limited to shallow depths of about 40m and that recharge is presumed to be small due to the crystalline nature of the rocks.

4.4.1 Hydrogeologic Characterisation

The Johannesburg area is underlain by the Basement Complex hydrogeologic terrain forming the distinct South African basement aquifer type. The specific geology underlying the inner-city consists of quartzite and shale lithology of the West Rand group of the Witwatersrand Supergroup almost split in the middle by the intrusive lavas & tuffs of the Klipriviersberg group of the Ventersdorp Supergroup. The Hospital Hill subgroup north of these intrusive lavas is mainly quartzite bedrock with shale while the Jeppestown subgroup just south of the intrusive rocks is mainly shale bedrock with quartzite subordinate. The area typically has an alternating shale & quartzite layer.

The lithology of the Witwatersrand Super-group typically has dips between 30 – 45 degrees to the south. Shale generally has a high porosity but low permeability due to fineness of its grain size. The Witwatersrand quartzite is prominently highly resistant, forming ridges that run in the west to east directions and becomes sandy soils when it is eventually weathered. These high ridges will possibly be recharge zones.

The study area can be distinctly divided into three thirds, where the northern third is underlain by the quartzite and shale of Hospital Hill subgroup, which have been intruded in the east-westerly direction by diabase igneous intrusion and contorted iron bed. The area is faulted. The dykes have since decomposed the middle third referred to as the Johannesburg graben valley, which consists of andesitic lava that is highly weathered to a depth of approximately 40m before becoming stiffer and less weathered with depth up to the bedrock. The highly decomposed lava mostly forms clays, which form an impermeable layer covered by transported soils deposits that can be up to 3m thick as observed at the greenhouse and Betrams borehole logs.

The southern third consists of medium grained quartzite alternating with arrenaceous shales of the government, and Jeppestown subgroups, which have been extensively intruded by diabase dykes and is thus highly fractured. Residual quarzitic soils found are not deeply developed and are overlain by transported soils of hillwash and aluminium origin. The inner-city is bounded on the north by the more solid stiffer quartzite of the Parktown formations, underlain by deeply weathered archean granites of the halfway House Dome. It is then bounded on the south by the less intruded and more resistant quartzite conglomerate roles of the Johannesburg subgroup of central rand group. The middle and southern thirds are then further bounded on the western side by an intrusive syenite dykes, which is highly resistant with a composition similar to that of granites.

There are three main aquifers identified in the study area, as shown in ***Table 3***. These are slate (metamorphosed shale), fractured quartzite (metamorphosed sandstones) and dolerite dykes of the lava. The confining units are the decomposed lava residual clays. The depth of weathering in the graben valley is approximately 45m, which dictates the aquifer thickness of the dolerite dykes. The main conduits of groundwater connecting the three aquifer units are the fractures, making the ground water occurrence in the system to be influenced mainly by secondary porosity. Pumping tests showed that the slate is a leaky aquifer while the dolerite and the fractured quartzite are confined aquifers. Abiye (2011) found that the flow mechanism is of diffusive nature and there is a decrease in water velocity with depth. Thus permeability of these crystalline rocks generally decreases with depth as more fresh bedrock is encountered.

The pumping test data for the drilled boreholes were analysed using the theoretical diagnostic plots of the time-drawdown relationships proposed by Kruseman and De Ridder (1990) and the theoretical analytical models from Van Tonder et al. (2002).

Table 3: Identified aquifer types within the study area

Borehole Site	Borehole Depth (m)	Main Aquifer Geology	Aquifer Type
Helpmekaar High	84	Black Slate	Unconsolidated **Leaky** aquifer
Barnato High	80	Black Slate	Unconsolidated **Leaky** aquifer
Yeoville Primary	72	Black Slate	Highly permeable dike in an otherwise poorly permeable aquifer
Green House	84	Dolerite	Single plane vertical fracture in a consolidated **confined** aquifer
Betrams skills centre	80	Dolerite with quartz veins	Consolidated **confined** fractured aquifer, double porosity type
Troyeville Primary	80	Quartzite	Unconsolidated **confined** aquifer
John Mitchell Primary	82	Quartzite and dolerite dyke	Single plane vertical fracture in a consolidated **confined** aquifer
Jules High School	90	Silt & Quartzite	Consolidated **confined** fractured aquifer, double porosity type
Bertha Solomons	80	Sand & Quartzite	Unconsolidated **confined** with partially penetrating borehole

4.4.2 Hydrologic System Characterisation

Water levels from the 9 boreholes that were drilled as part of this study were measured over a period of 2 years (October 2017 to October 2019). The static water levels showed an overall trend of system recharge over the slate and fractured quartzite aquifers, indicating that the topographically high areas on each side of the graben valley constitute the recharge zones of the study area. The average precipitation over the two years was 619.01mm.

The areal extent of the part of basin covered by the study area is 12.37km^2. Two main drainage area systems occur in the area, with the middle of the inner-city being a ridge that divides the two systems. The Vaal River System tributaries drain in a predominantly southerly to south-westerly direction, while the Limpopo River System tributaries drain in a northerly to north-westerly direction.

The eye of the Jukskei River, which is a major tributary of the Limpopo River basin originates on the eastern part while the eye of the Braamfontein Spruit originates on the north western part of the area. On the south eastern part of the inner-city two springs that form the eyes of the Natalspruit and Rietspruit tributaries respectively and which drain to the Vaal River System were previously observed. All these four springs have since been covered by construction developments. The area is densely built and densely populated with mainly urban infrastructure land use.

According to Barnard (2000), ground water level generally occurs between a depth of 10 and 25m below surface in the West Rand Group. The actual static water levels that were measured from the boreholes indicates an average depth of 11.21m below surface, which collaborates well with the observed water marks in buildings basements. From the observed potentiometric surfaces, ground water is expected to flow in the east to west direction.

Based on information from old Johannesburg maps, consultants' geotechnical reports (e.g. Seyler et al., undated; McCarthy, 2010; SRK Consulting, 2016), De Beer (1965), google maps and the field work done in this study, a simplified conceptual model of the inner-city is shown in ***Figure 15*** below.

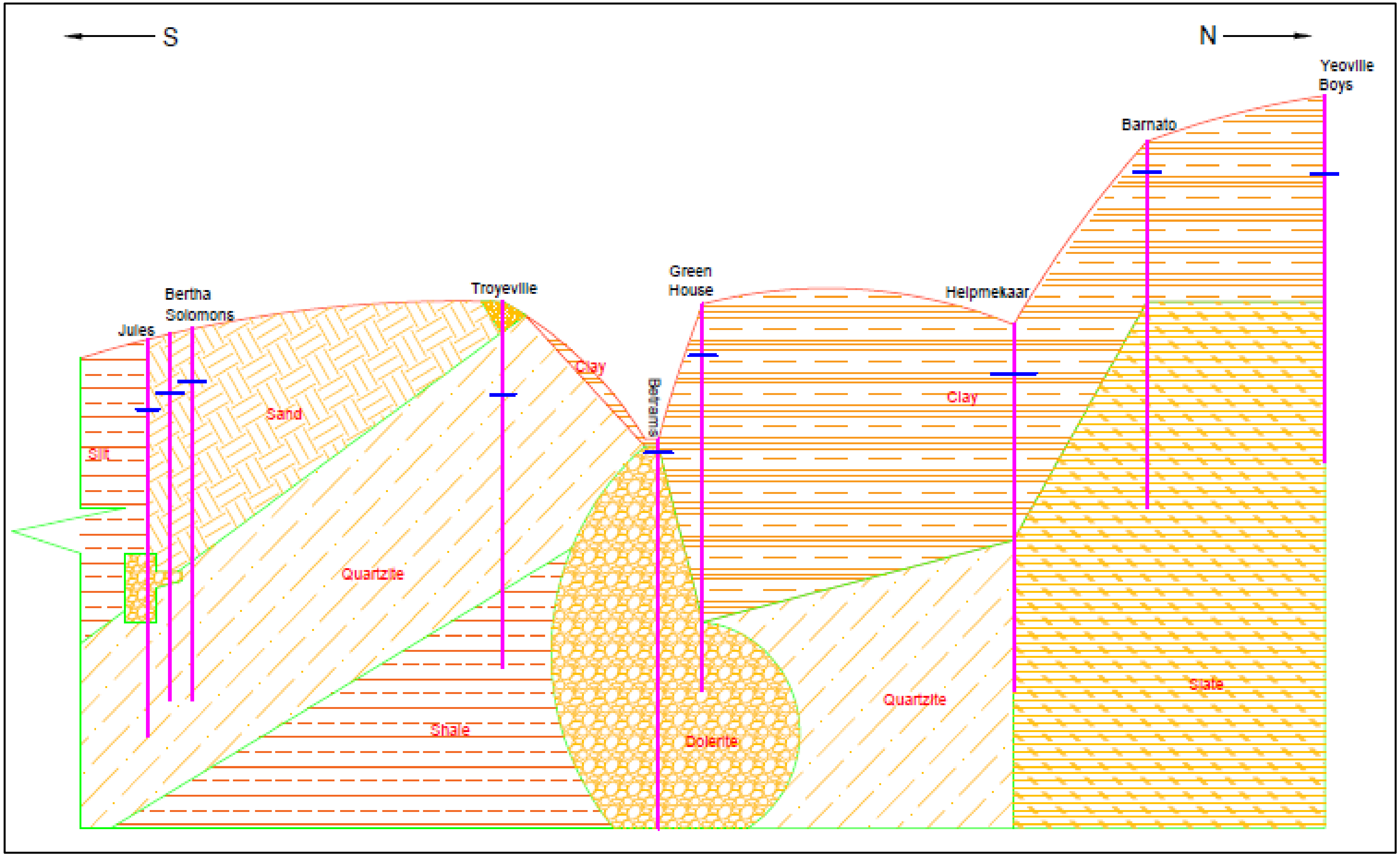

Figure 15: Cross-section in the South-North direction (Blue lines are static water levels – Oct. 2018)

4.5 Numerical Groundwater Flow Simulation

4.5.1 Model Design

The numerical groundwater flow simulation was developed using information from the conceptual hydrogeological model above. The FE-method-based-software, SPRINGfree 4.32 (König et al., 2017), was used to analyse the simplified representation of the groundwater system. The model was developed with the purpose of forecasting the system's response to future stresses, such as predicting how much groundwater will have to be abstracted from the aquifer in order to lower the water table levels to below the specified depth of building basements in the study area. Thus, the model was calibrated in order for it to be used as a predictive tool and a model confidence level class 2 (see Barnett et al, 2012) was targeted. The simulation was done in a 2D areal, steady-state mode, assuming a fully saturated zone.

To delineate system boundaries, the position of the existing physical boundaries of the more resistant quartzite ridges in the north and south of the study area and Syenite dyke on the south western part were used to set positions of 'no-flow' hydraulic boundaries and define the model domain, as shown in ***Figure 16***. The eastern and north-western boundaries were set up as hydraulic boundaries by using known water levels and geographical positions of those measured points. The elements were all assigned three attributes, they are: aquifer thickness, conductivity and areal seepage (recharge rate). The average porosity was set at 0.20. This model design ignored any groundwater-surface water interaction that may occur, with the aquifers mostly showing to be confined or leaky.

According to Leketa et al. (2018), the recharge estimate in the Hospital Hill shale and Government quartzite groups of the Witwatersrand Supergroup is 2.5%. This works out to about 15.5 mm/year groundwater recharge. From the monitoring of the nine drilled boreholes in this study, water level measurements were done at regular intervals and an average recharge rate of 190 mm/year was observed. This shows that the area has a high artificial recharge rate caused by municipal infrastructure leakages. The recharge rate value of 15.5 mm/ year has been used in the model, to be conservative and optimistically foreseeing the high artificial recharge reducing over the years to come as infrastructure maintenance improves.

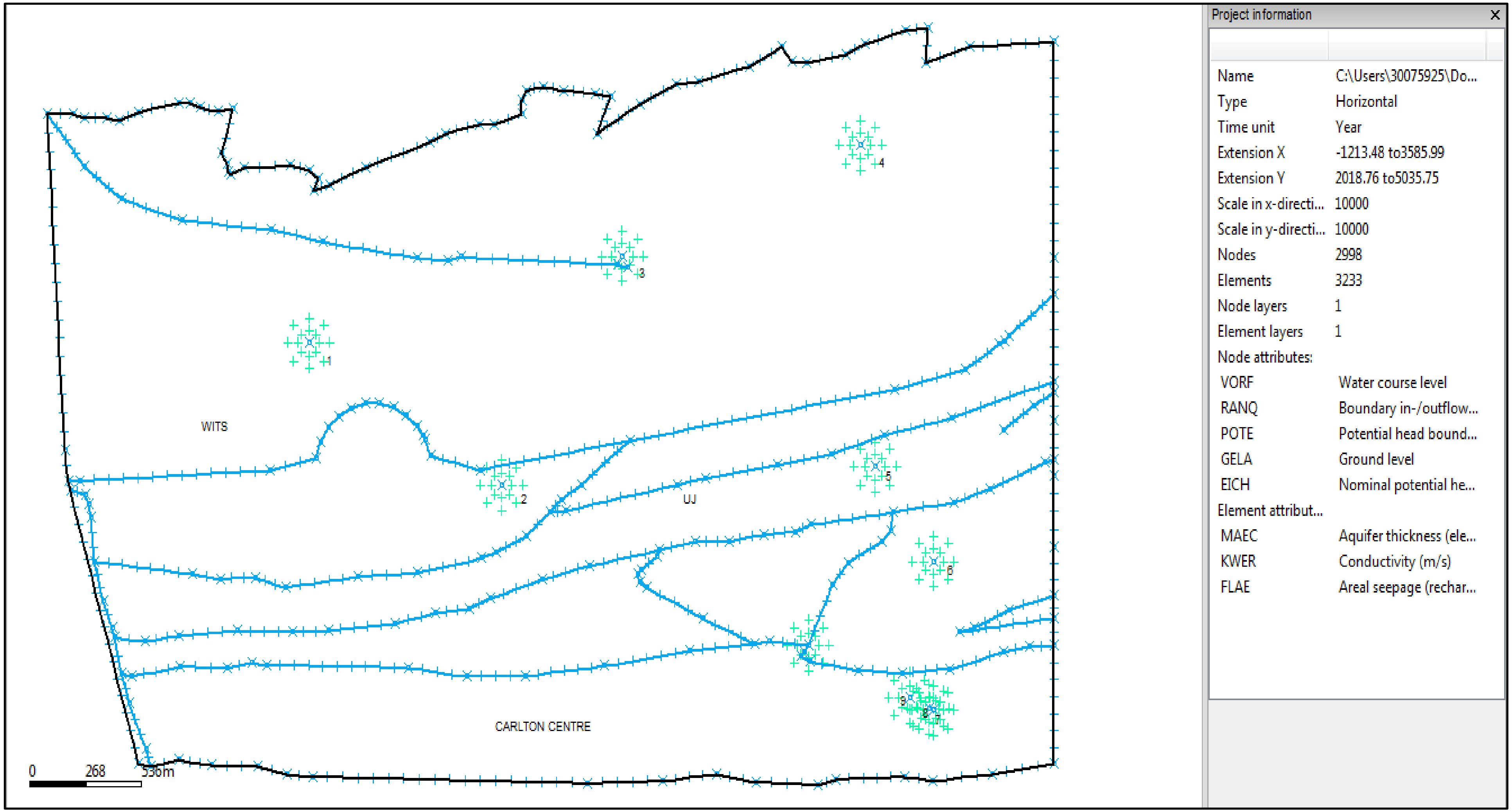

Figure 16: Model domain showing system boundaries and parameters used

The structures within the model boundary were delineated using the geology and geotechnical shape files obtained from the city's GIS database. Two of the water courses which have their eyes originating within the study area are also represented within the shape files. The model contours traced the boundaries of these structures and then the nodes and elements (triangles and quadrangles) were generated from the contours. Ground level elevations at 1m contour interval were obtained from the available cadastre database and were superimposed on the model. These were also checked and validated with Google Earth. The aquifer thickness was assumed to be constant across the different types respectively (***Table 3***). The slate aquifer thickness was set at 150m and the dolerite and quartzite aquifers set at 100m.

The conductivity values of the geological sections were obtained from the pumping tests that were carried out on each of the nine boreholes that were drilled. The values of conductivity were aggregated and assumed to be constant across the respective hydrogeological units as shown in ***Figure 17***. The hydrological boundaries of the model comprised of the specified no-flow-flux boundaries at the north, south and south western ends of the model (i.e. Q = 0 m^3/year) and specified heads at the eastern and western ends, based on field measurements of already existing boreholes and data from a drilling contractor.

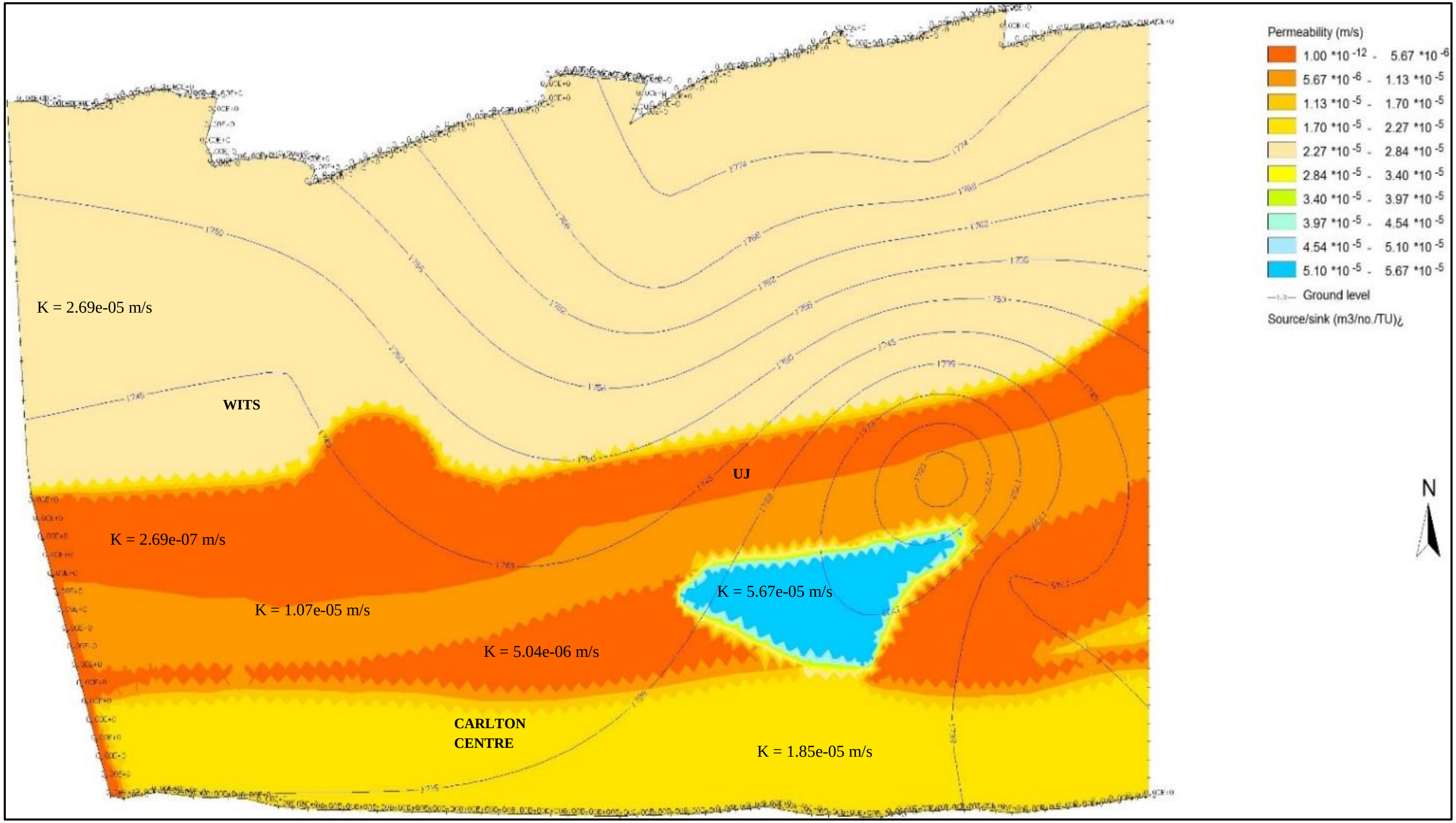

Figure 17: Model domain with natural ground level elevations and conductivity values per hydrogeological unit

4.5.2 Model Calibration

Models need to be calibrated in order to check if the simulated values compared reasonably well with the fields measurements. The input parameters that were entered into the model were ground level elevation (masl); conductivity (m/s); aquifer thickness (m); potential head boundary condition (masl); boundary in-/outflow (m^3) and water course level (masl).

It can be seen from the simulation of current situation, scenario 0, (i.e. no abstraction from the drilled boreholes) and assuming 0.015 m/a recharge, shown in ***Figure 18***, the middle third of the study area has an average potentiometric surface of 6.3m below ground level, which is shallower than the average basement depth of 8 m. The water level in that section ranges between 0m and 18.6m below ground. This results in a state of constant flooding of the buildings' basements in the CBD. The building owners are currently handling the flooding by typically collecting the seepage water into a sump and then pumping it with an automated submersible pump as waste water. In ***Figure 18***, negative values indicate seepage above ground level, while positive values show the depth of the water table below ground.

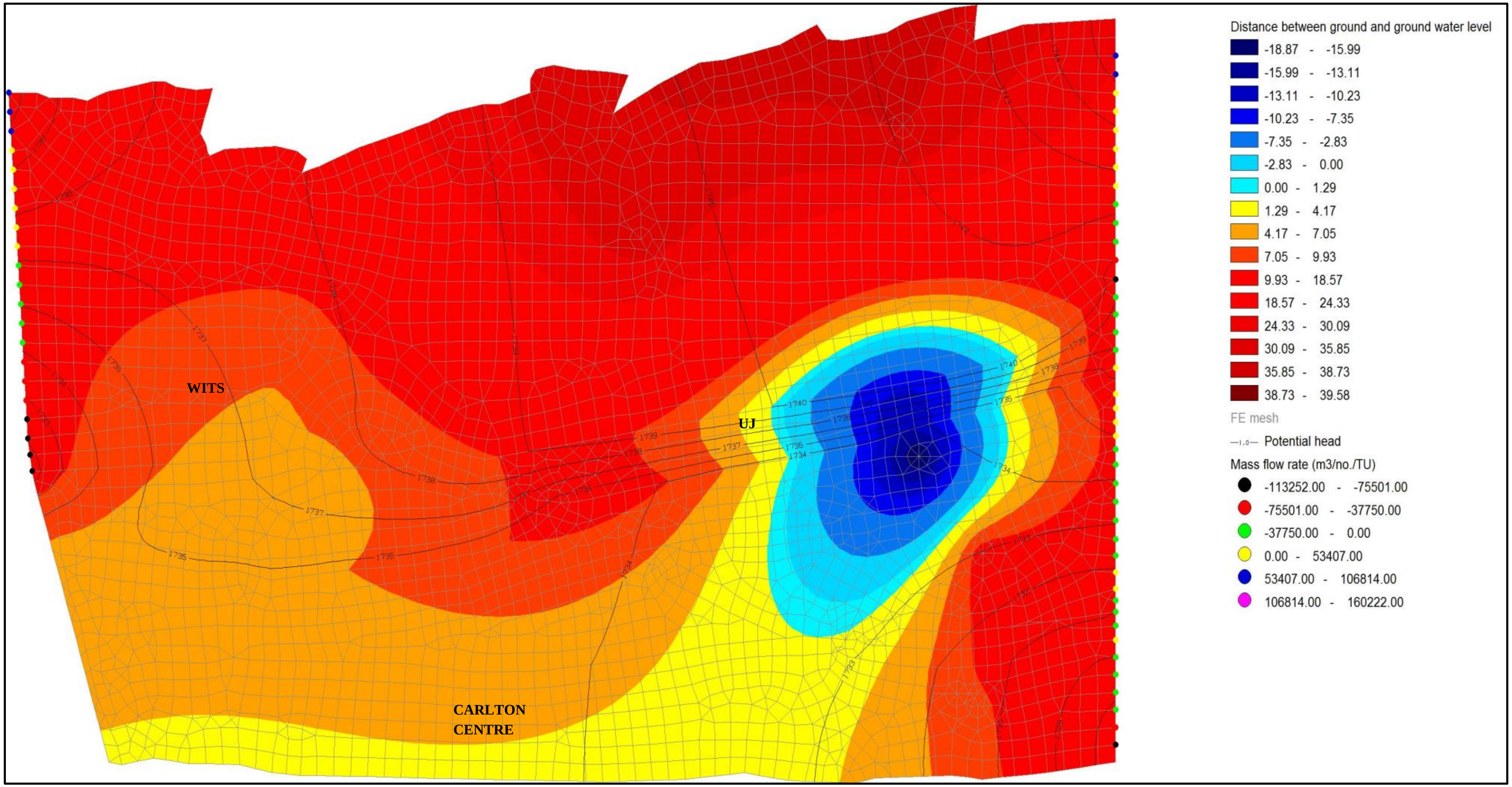

Figure 18: Model simulation showing current situation (scenario 0)

In this study, the measured static water levels of the boreholes were considered as the observed potentiometric surface and used for calibration of the model of the current scenario. This was done by checking the difference between the calculated model values of the potential head at the corresponding nodes of boreholes and the field-measured static water levels in the boreholes, as a ratio to the assumed aquifer thickness. The absolute percentage error values range from 1.1% – 18.4% as shown in ***Table 4***.

Table 4: Correlation between the measured water levels and the calculated potential head

Borehole Site	Ground level elevation (masl)	Aquifer thickness, b (m)	Final Static Water Level (masl)	Calculated potential (masl)	Percentage error
Helpmekaar High	1745	150	1740.1	1737.34	1.8%
Barnato High	1773	150	1767.35	1739.75	18.4%
Yeoville Primary	1778	150	1761.85	1741.56	13.5%
Green House	1748	130	1736.83	1737.94	1.1%
Betrams skills centre	1715	130	1712.05	1734.17	17.0%
Troyeville Primary	1745	100	1723.77	1733.02	7.1%
John Mitchell Primary	1740	100	1727.68	1730.84	3.2%
Jules High School	1740	100	1725.01	1730.94	5.9%
Bertha Solomons	1740	100	1728.47	1731.35	2.9%

***masl = metres above sea level**

Further to the calculation of the percentage errors above, a sensitivity analysis was done where the initial input parameters for aquifer thickness and conductivity were varied (up or down by up to 50%) in order to observe the extent to which each parameter influences the calculated potentials. The results of the sensitivity analysis show that both the thickness and conductivity of the aquifer contribute a very small percentage of as much as 0.05% to the changes in the water levels, with the aquifer thickness contributing more to this variation. In terms of length, this variation could account for about 0.87m for a given potential, which does not significantly alter the percentage errors.

4.5.3 Aquifer Potential

The total yield potential within the section of basin was estimated using the storage coefficient (S) and aquifer thickness. An estimated aggregated specific storage coefficient of 0.2% for the confined aquifer (from Johnson, 1967) was used.

$$\text{Aquifer}_{\text{storage}} = \text{Area} \times \text{b} \times \text{S}$$

$$= 12.37\text{km}^2 \times \left(\frac{1000\text{m}}{1\text{km}}\right)^2 \times 100\text{m} \times 0.002$$

$$= 2.47\ \text{Mm}^3$$

This is total yield potential of the area modelled.

4.5.4 Predictive modelling

The model was then subsequently used to simulate groundwater levels that would result from constant pumping of the drilled boreholes in order to evaluate pumping required to reduce the water table by 1m. Model verification where the changing groundwater levels could be compared with measured data after pumping could unfortunately not be done, due to unavailability of such data as the boreholes are not operational yet.

Recommended abstraction rates were given by the Council for Geoscience (2017), shown in ***Table 5***, and are slightly more conservative than the calculated long term sustainable abstraction rates from the pumping tests of each borehole. This is ascribed to the fact that the methodologies used to calculate the sustainable yields are inherently assuming a structured aquifer instead of the unconsolidated aquifers found in the study area. Roughly, a factor of safety of 1.2 is deduced from the data. These yields can be even higher if pumping is assumed to be only for 8 hours per day and thus giving the borehole sufficient time to recover.

Table 5: Borehole yields from the pumping test and the recommended pumping rates per annum

Boreholes	Depth (m)	Yield (l/s) for 24hrs	Recommended abstraction rate (m^3/a)
Helpmekaar School	84	1.2	37 843.2
Barnato Park High School	80	0.9	28 382.4
Yeoville Boys Primary School	72	3.5	110 376.0
Green House	84	0.3	9 460.8
Betrams Skills Centre	80	1.5	47 304.0
Troyeville Primary School	80	2.0	63 072.0
John Mitchell Primary School	82	0.6	18 921.6
Jules High School	90	0.6	18 921.6
Bertha Solomon Rec Centre	80	1.8	56 764.8

Pumping Scenario 1:

In simulating scenarios, the first scenario considered is the withdrawal of groundwater from the aquifer at the recommended abstraction rates, as shown in ***Figure 19*** below. In pumping scenario 1, the water table level will generally stabilise at an average depth of 7.8m below ground. Thus, the water table level would slightly decline and vary between a minimum of 0m to a maximum of 14.7m below ground surface, which is not sufficient to completely prevent flooding in building basements in the CBD. This is equivalent to an average decline of 1.5m in the potentiometric surface slope across the study area as compared to scenario 0, where the average depth is 6.3m below ground.

Some buildings in the Doornfontein suburb such as those of the University of Johannesburg (UJ) would now have very little, if any, flooding as the average basement in the area is 3m deep and the water table level would now be varying from between 0m and 6.45m below ground (thus, the average water table level of 3.5m below ground). To the right of Doornfontein suburb, at point A, the groundwater is still decanting which is where the eye of the Jukskei River daylights.

The volume of water that will be available for supplementing municipal supply, given pumping scenario 1 at the recommended abstraction rates (and assuming interconnected aquifers), would be the water released from storage:

$$\begin{aligned} \Delta V &= \text{Area} \times \Delta H \times S \\ &= 12.37\text{km}^2 \times \left(\frac{1000\text{m}}{1\text{km}}\right)^2 \times 1.5\text{m} \times 0.002 \\ &= 37\,110\ \text{m}^3/\text{a} \end{aligned}$$

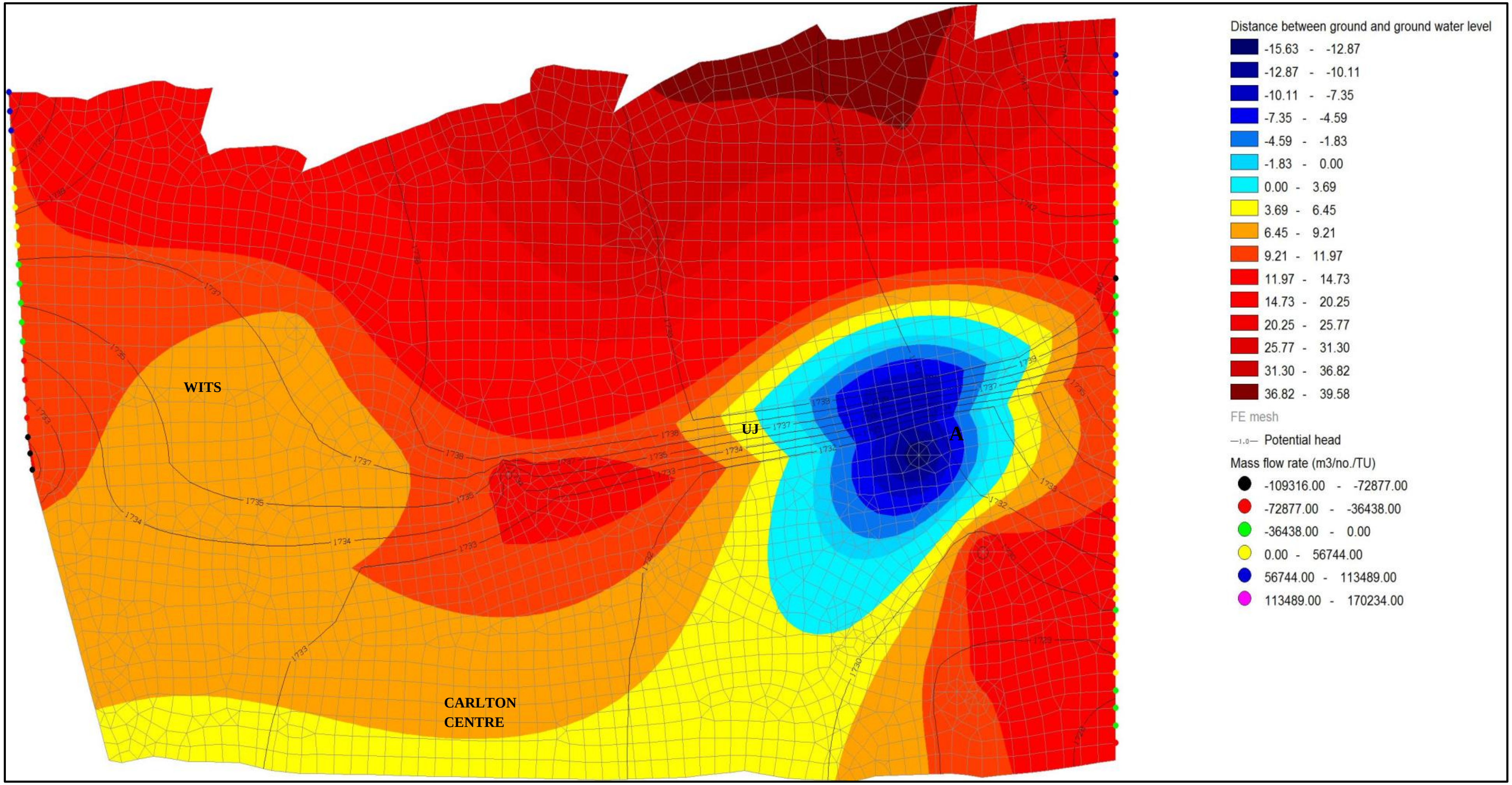

Figure 19: Model simulation showing pumping scenario 1 at recommended abstraction rates

Pumping Scenario 2:

In scenario 2, withdrawal is simulated by pumping the 9 boreholes at the calculated long term sustainable rates (= recommended rates multiplied by factor of safety of 1.2). The model simulation results are presented in ***Figure 20***. This would drain down the potentiometric surface by an average of 2.3m and would result in an average water level depth of 8.6m below ground (compared to scenario 0, where the average depth is 6.3m below ground) in the CBD to Doornfontein suburbs. The varying water level in scenario 2 is between a minimum of 0m to a maximum of 20.59m below ground surface.

If scenario 2 would occur, which is somewhat over-pumping of the boreholes, then the amount of groundwater released from storage that would be available for supplementing municipal supply would be:

$$\begin{aligned} \Delta V &= \text{Area} \times \Delta H \times S \\ &= 12.37\text{km}^2 \times \left(\frac{1000\text{m}}{1\text{km}}\right)^2 \times 2.3\text{m} \times 0.002 \\ &= 56\,902\ \text{m}^3/\text{a} \end{aligned}$$

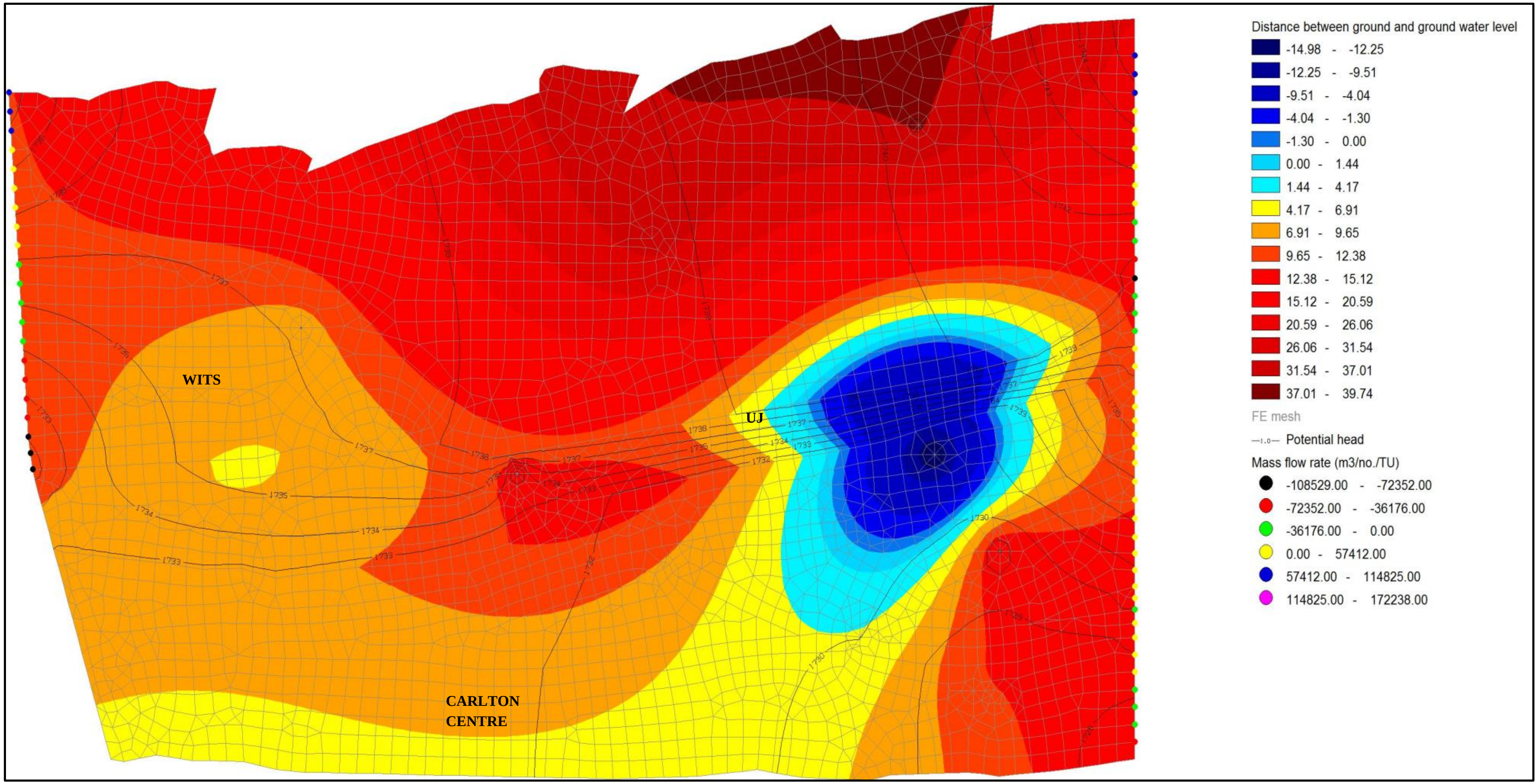

Figure 20: Model simulation showing pumping scenario 2 at calculated sustainable yield rates

Pumping Scenario 3:

For governance and monitoring purposes, a third hypothetical pumping scenario was created where the residents are encouraged to drill their own private boreholes and withdraw hypothetically at set respective sustainable yields for each hydrogeologic unit. The boreholes are located at various random locations across the model domain. This is a scenario that is likely to occur as the threat of drought and water restrictions increases. Under this scenario, the simulation indicates that if 20 boreholes were simultaneously withdrawn, then the overall average water table level in the CBD would decline by 3.3m in comparison to the current situation. In this scenario, the water table level in the CBD would be between 0m and 21.5m below ground level as shown in ***Figure 21***. If this scenario were to materialise in reality, then one needs to consider what impact that would have on the surface water that emerges in the area. It can be seen from the pumping scenario 3 that there could be some impact on the ground-surface water interaction in terms of groundwater seepage that decants on the eastern side of the area and emerges as the eye of the Jukskei River just north east of the Betrams Skills Centre borehole.

In scenario 3 the amount of groundwater released from storage that would be available for supplementing municipal supply would be:

$$
\begin{aligned}
\Delta V &= \text{Area} \times \Delta H \times S \\
&= 12.37\text{km}^2 \times \left(\frac{1000\text{m}}{1\text{km}}\right)^2 \times 3.3\text{m} \times 0.002 \\
&= 81\,642\ \text{m}^3/\text{a}
\end{aligned}
$$

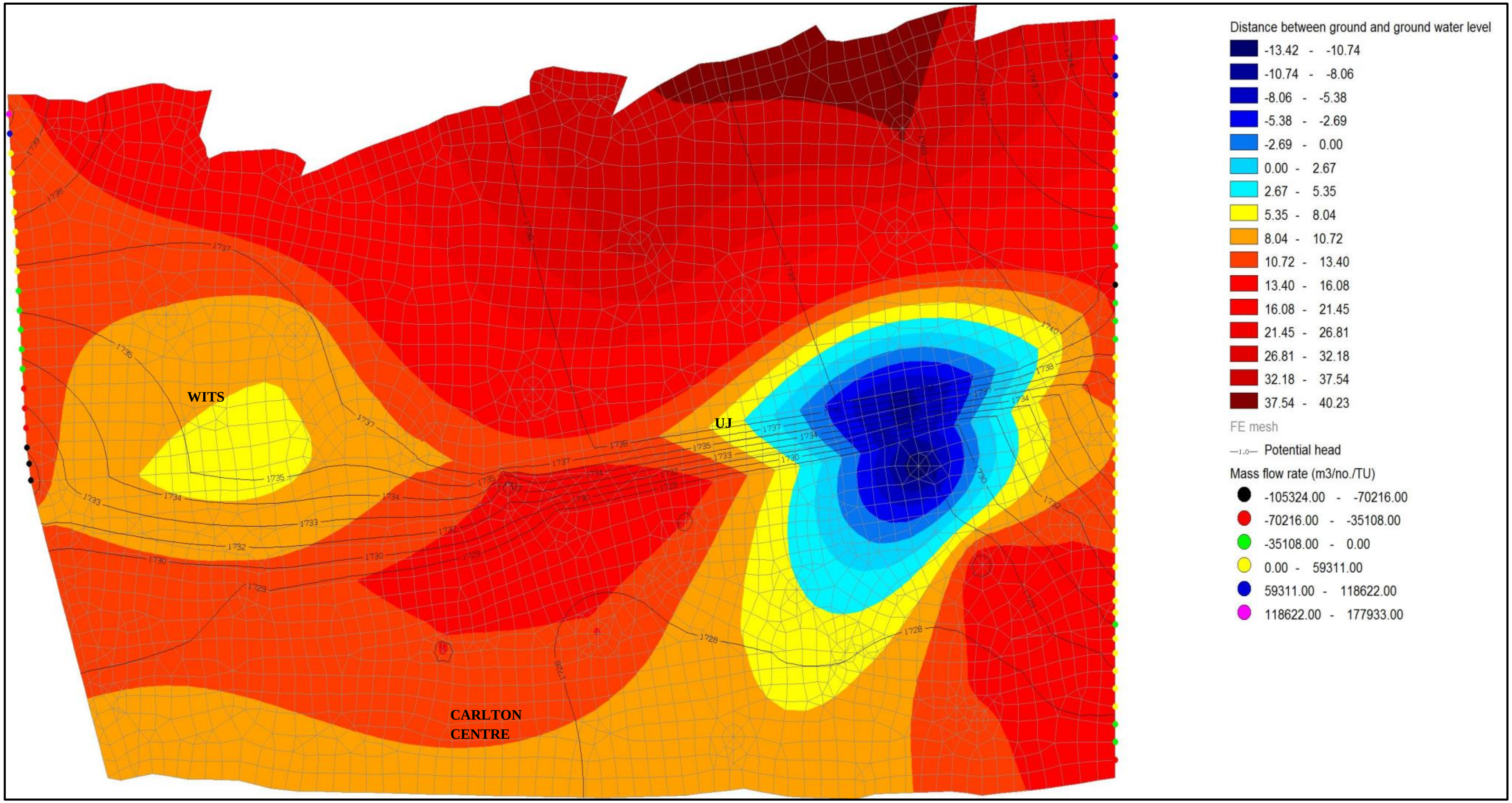

Figure 21: Model simulation showing pumping scenario 3 (20 boreholes) at calculated sustainable yield rates

4.6 Proposed Uses of the Abstracted Groundwater

The results show that the groundwater usage is a viable alternative water source that has a total reserve of 2.47 Mm^3 available as a complementary source to the Johannesburg inner-city residents. This water is sustainably available at an average rate of 56 902 m^3/a and conservatively recommended to be abstracted at an average of 37 110 m^3/a. In the main, this water can be used for water closets, for filling swimming pools and for irrigation supply purposes. The boreholes are mostly drilled on sports fields or open ground and thus a booster pump will be required in addition to the borehole pump. This booster pump would also be required if water is taken up to roof-tops for storage in the multi-storey commercial properties.

<u>Water Use 1: Water closet and urinal flushing at schools; Roof/ urban gardens</u>

The water demand for flushing water closets and urinals is estimated per type of establishment by Nozaic and Freese (2009). A total estimate of 29 600 L/d per school is used for the water demand calculation. This was obtained by considering an estimate of 800 learners per school, then multiplying the number by the daily demand flow of 37 litres per learner (Nozaic and Freese, 2009). This means that a 10 000L Jojo tank could be filled up to 3 times a day and a booster pump used to supply the toilets from the tank, if the tank is on the ground.

A similar calculation can be done for student boarding houses of about 400 occupants and an estimated daily demand flow of 110 litres per person. A total estimate of 44 000 L/d per building is obtained for the water demand. This translates to 16 060 m^3/a. This demand would be met by most of the boreholes drilled in this study, with the exception of the Green House borehole whose recommended abstraction rate is below this demand.

The following life-cycle costing can be done for the asset, assuming a 10 year life span. ***Tables 6 & 7*** below show the life-cycle costing for a solar powered-system and an electric-powered system respectively.

For an electric-powered system, one must additionally consider the electricity tariff in the operational costs. The electricity tariffs here have been conservatively estimated to increase at an annual rate of 14% per annum for the next 10 years. Looking at the current economic trajectory and the tariff increase applications that have recently been submitted by the energy utility company, this is a conservative estimate depending on what the National Energy Regulator would approve in the next 10 years.

Table 6: Life-cycle costing of a solar-powered borehole pump system

Item No	Description of Item		Unit of Measure	Quantity	Rate (ZAR)	Amount
1.	***Project Implementation***					
1.1	Submersible solar pump with motor and controller box (3.0 m^3/h)		No.	1	30 000	18 000.00
1.2	Associated borehole fittings (including submersible cable, rope, base plate)		Sum	1	2 500	2 500.00
1.3	Supporting structure/ base 42.5 MPa concrete footing		No.	1	5 500	5 500.00
1.4	10 000L Tank		No.	1	13 000	13 000.00
1.5	Solar panels stands (poles + mounting frames) with securing bracket(s)		Sum	1	5 500	5 500.00
1.6	Solar Panels (300 W)		Sum	4	2 600	8 400.00
1.7	Solar Booster pump		No.	1	10 000	5 800.00
1.8	Heavy duty manhole with cover		No.	1	4 500	3 500.00
1.9	Consumables	32mm HDPE pipe (Pe 100)	m	100	10	1 000.00
		Electrical cable	m	100	60	6 000.00
		Other (cable termination, tank starter kit, etc.)	Sum	1	800	800.00
1.10	Retrofitting and separation from municipal supply		Sum	1	7 000	7 000.00
1.11	Clear view perimeter fence with spikes and lockable gate		m	16	800	12 800.00
					Sub-total Project Implementation	89 800.00
					Consultation and Design (@8%)	7 184.00
					Sub-Total	96 984.00
					10% Contingencies	9 698.40
2.	***Operation and Maintenance***					
2.1	Water Quality testing at a SANAS accredited laboratory		Annual	10	3 500	35 000.00
2.2	Mechanical equipment replacement and quality monitoring (percentage of capital amount)		2.5% / a	10		25 475.50
					Sub-Total Operational & Maintenance	60 475.50
				Gross Total (including VAT)	**R 167 157.90**	

Table 7: Life-cycle costing of an electric-powered borehole pump system

Item No	Description of Item		Unit of Measure	Quantity	Rate (ZAR)	Amount
1.	***Project Implementation***					
1.1	Submersible electric pump with motor and controller box (3.0 m^3/h)		No.	1	10 000	10 000.00
1.2	Associated borehole fittings (including submersible cable, rope, base plate)		Sum	1	2 500	2 500.00
1.3	Supporting structure/ concrete footing		No.	1	5 500	5 500.00
1.4	10 000L Tank		No.	1	13 000	13 000.00
1.5	Booster pump		No.	1	4 000	3 500.00
1.6	Heavy duty manhole with cover		No.	1	4 500	3 500
1.7	Consumables	32mm HDPE pipe (Pe 100)	m	100	10	1 000.00
		Electrical cable	m	100	60	6 000.00
		Other (cable termination, tank starter kit, etc.)	Sum	1	2 000	2 000.00
1.8	Retrofitting and separation from municipal supply		Sum	1	7 000	7 000.00
1.9	Clear view perimeter fence with spikes and lockable gate		m	16	800	12 800.00
					Sub-total Project Implementation	66 800.00
					Consultation and Design (@8%)	5 344.00
					Sub-Total	72 144.00
				10% Contingencies		7 214.40
2.	***Operation and Maintenance***					
2.1	Water Quality testing at a SANAS accredited laboratory		Sum	10	3 500	35 000
2.2	Additional power consumption from 1kW borehole pump (8 hours for 200 days per year). Based on 2019 rates and assuming 14% inflation.		kWh/yr	1 600	0.936	28 959.53
2.3	Additional power consumption from 0.75kW booster pump (8 hours for 200 days per year). Based on 2019 rates and assuming 14% inflation.		kWh/yr	1 200	0.936	21 719.65
2.4	Mechanical equipment replacement		2.5% / a	10		18 950.60
					Sub-Total Operational & Maintenance	104 629.78
			Gross Total (excluding VAT)	**R 183 988.18**		

Water Use 2: Sports fields' irrigation for beautification

The costs under this alternative water use will be the same as above for both the solar and the electric powered system(s), except that there will be no retrofitting required to convey the water to the buildings or roofs, as the boreholes are located next to the sports fields.

The water may also be used for aquaponics plant systems, industrial manufacturing and cleaning purposes, etc. The above basic costs would be applicable in these uses as well, with the designs of the systems differing from site to site based on specific use. Thus, the costs above can be considered as sufficient basic guideline for minimum applicable costs.

With the nine boreholes drilled in this project, 56 Million litres per annum can be sustainably provided. Considering that the current supply of water in the Johannesburg inner-city supplied by the Yeoville reservoir is approximated to be about 100Ml/day, and taking into account that physical loses (portion of non-revenue water) in the system are currently at about 20%, the demand can therefore be 80Ml/day. It follows therefore that it is more prudent that groundwater resource usage is done in a decentralized approach instead of investing in infrastructure for utilisation of bulk supply, as the groundwater resource available for supply is a minute fraction of this demand. However, as the demand increases, the price of water escalates and more boreholes are drilled by both the city and the private consumers. This will heighten the need for comprehensive groundwater resource management systems.

5. DISCUSSION

The study sought to respond to three main research questions which aimed at establishing whether sufficiently large quantities of groundwater are available in the Johannesburg inner-city in order to develop a supply source that can be used to supplement the current municipal supply that is 100% reliant on surface water sources, which are currently strained as the high demand continues to soar.

At the onset of the investigation it was established that there is groundwater seepage that is viewed by many property owners and managers as a nuisance. The seepage of groundwater into building basements is a common occurrence that threatens the safe occupancy and functionality of these basements. The aim of this study can be summarised as to create a conceptual hydrogeological model of the area in order to determine quantities of groundwater available and possible uses of this groundwater after withdrawal in order to alleviate the problem of flooding of building basements. Three research questions are answered by this research, viz. how much groundwater is available to be safely abstracted within the Johannesburg inner-city to ensure safe water table levels for building basements? What are the characteristics and recharge dynamics of the aquifers underlying the study area? What is the feasibility of utilising this groundwater resource to supplement the potable municipal supply?

In the literature review, the study looked at the different techniques that are used to characterise the aquifer system in order to delineate the groundwater resource. In the current study, literature, which includes past borehole and geotechnical data, geological field surveys, drilling logs, maps, together with drilling and pump testing of boreholes were used to establish the hydrogeological environment (properties, distribution and structure of the rocks). Moreover, the literature was also used to assign the aquifer parameters in order to determine the occurrence of water in the study area.

The literature review also highlighted that earlier work done (De Beer, 1965; Barnard, 2000; Abiye, 2011; and Dippenaar, 2015) focused on a regional scale of the Greater Johannesburg area. Thus, this current work sought to zoom in and be site-specific to the Johannesburg inner-city. The findings confirmed the previous research in that groundwater circulation has been indeed found to be limited to shallow depths of less than 40m as suggested by Abiye (2011) and has specifically been found to be circulating at an average water strike of 39m.The static water level of the boreholes has been measured to be 11.21m below ground, indicating the largely confined aquifer type identified in ***Table 3***.

The water levels also corroborate with the regional groundwater level given by Barnard (2000), generally occurring between a depth of 10m and 25m below surface in the West Rand Group. Therefore, the water is confined at depths of about 40m and given a path, it would rise to an average of about 12 m. Post the development of the inner-city with the presence of deep basements below ground, the water level was further pressurised and displaced upwards to an average potentiometric surface level of about 7m below ground. The yields of the boreholes in the study area were also largely determined to be below 2l/s as indicated by Barnard (2000), with the exception of Yeoville Boys' Primary School and Troyeville Primary School, which are interestingly both situated on elevated ridges relative to their surroundings (see ***Figure 15***).

5.1 How much groundwater is available?

This study sought to look at how much the water table would generally decline, relative to the average depth of the basements, when pumping is at the recommended safe yield and subsequently how much groundwater resource would be available to supplement the municipal water supply. The survey, exploration, borehole pumping tests and numerical modelling carried out in this study indicated that:

- Based on the sample of the buildings observed, most of the basements (60%) in the inner city experience occasional to regular flooding. These 'flooded basements' comprise those that are two levels deep (about 6m) and/or more, with the average building basement being 8m deep. Based on the observations made of the water table level around these basements, and that most frequently occurring basements are the two levels deep, a decline of at least 1m is required to ensure safe water table levels for the building basements. Some of the building basements that are deeper than the 6m will not be completely cleared of the risk of flooding, depending on where they are located in the inner-city relative to the slope of the water level.
- There are recommended and actual calculated abstraction rates. The methodologies used in interpreting the pump tests were developed mainly for structured aquifers, and not for the combination of alluvial, unconsolidated and fractured aquifer found in the study area. Therefore, the calculated abstraction rates were adjusted down based on experience and judgement as these methodologies tend to overestimate the sustainable yields with an average "factor of safety" of 1.2. If all the 9 drilled boreholes are subject to pumping as per the recommended abstraction rates, then a volume of 56 Ml/a would be available as a supplementary resource in the water supply mix and an average drop of 2.3m in the water table level is a cumulative effect that would result, assuming all the boreholes are in constant effective usage. The 2.3m drop in the water

table level would result in about 30% of the building basements in the surveyed sample exonerated from the risk of flooding.

- The volume is minute (0.2 %) compared to the current water demand of 80Ml/day supplied by the local reservoir in that area. Instead of viewing the groundwater resource as a completely alternative supply to meet the current high water demands, the city should rather view this groundwater as a complementary resource to build resilience into the system and mitigate against the increasing risk of water shortages posed by climate change related impacts. Water scarcity is great threat to the city and the nation as a whole. The probability of water shortage is ever increasing due to increasingly stressed surface water sources as a result of currently poor implementation of water resource management, exacerbated by climate change effects. As a result, putting in place decentralised infrastructure that would enable the city to tap into the groundwater source is a strategic action to take.
- It is strongly recommended that the individual commercial properties, such as the student boarding houses (shown in section 4.6), be retrofitted for groundwater reclamation as the water would be more than sufficient at a localized level for non-potable uses.
- Distribution of boreholes is skewed towards the eastern side of the study area due to available open space for drilling rig as well as for the security of the borehole equipment, once operational. This could affect the effectiveness of pumping of the boreholes to get a desired uniformly distributed reduction of the water table level.

5.2 Characteristics and recharge dynamics of the aquifer(s)

The work presented in the study also sought to identify the specific characteristics of the aquifers underlying the Johannesburg inner-city as well as explore their recharge dynamics. From the hydrogeological characterisation part of this study, it was established that in line with the general borehole yields of less than 2l/s that are expected for fractured and intergranular and fractured aquifers typical of the geology found in this area (Barnard, 2000), the specific structural geology of the area dictates the borehole yields of average 1.4l/s. Topographically high areas on each side of the graben valley constitute the recharge zones of the study area. The Yeoville Boys' Primary School and Troyeville Primary School, which are situated on these high altitudes on either side have recorded the highest yields of 3.5l/s and 2.0l/s respectively.

The borehole development, shown in ***Figures 5 – 13***, revealed that the area has mainly confined aquifers made up of quartzite and black slate overlain by clay in the northern third. The central third (graben valley) is mainly made up of fractured dolerite with quartz veins, while the southern third is made up of quartzite underlain by shale and overlain by silty sands. The shale and clay tend to be confining layers in this hydrostratigraphy. The southern third is the most built-up, densely-populated and sealed up in terms of land use patterns.

On average, the aquifer is located at a depth of 50.5mbgl, based on measured depth of water strike. The exception is along the floor of the graben valley, which runs in the west-easterly direction where the aquifer, made up of weathered dolerite, is located at an average depth of 41mbgl. In these aquifers, the influence of the primary porosity is negligible, as the fractures in the rocks make the rock more permeable than it usually would be. Moreover, the structural features control the occurrence of aquifers (Barnard, 2000).

In terms of recharge dynamics, the static water levels of boreholes were measured over a total period of two years without any withdrawal occurring from the drilled boreholes, and it was observed that the boreholes are being artificially recharged at an average rate of about 0.19 metres per annum. This is considered artificial recharge, and is indicative of leaking water services infrastructure, as the natural recharge is expected to be 0.0155 m/a (Leketa et al., 2018). The boreholes were not yet equipped and operational at the time of the conclusion of this study, and hence the effects of pumping could not be monitored and hence verify the predicted results by the model.

5.3 Feasibility of utilising the resource

Currently many building mangers in the inner-city of Johannesburg are discarding the groundwater that seeps into the building basements as wastewater into the sewer system and into the storm run-off drainage system. The fact that under the current scenario, a natural recharge has been observed means the situation will 'deteriorate' if the aquifer is not stressed. From the commercial building point of view, if a typical basement has groundwater seepage of 2l/s decanting and filling a 16m^3 collection sump of about 2m deep, the required pump to keep the basement dry would be about a 1kW pump running for 12 hours per day. This would result in a consumption of 4 380 kWhr/yr, which equates to about R4 100 per annum in pumping costs (based on 2019 electricity tariffs). This cost will be higher with smaller collection sumps, or with a higher groundwater seepage rate and with an increase in the electricity tariff over time. Over a period of 10 years, with an assumed conservative annual tariff increase rate of 14%, this pumping cost will add up to a total of about R80 000.

From the initial chemistry analysis, the water is mostly suitable for drinking purposes, with the exception of Yeoville Boys Primary School, which showed iron and manganese levels that are above standard limits. Later tests conducted in June 2019 however showed iron levels that were within limits. However suitable the water may be, the City of Johannesburg firmly holds a position that this water should not be used for drinking purposes until a fully-fledged quality monitoring system is in place and the associated localized treatment systems are also in place where necessary. For the purposes of the currently recommended usage, this supplementary groundwater resource is to be used to ease the demand on the municipal water supply by off-setting water used for irrigation and flushing of water closets only. The total water demand estimate of 29 600 L/d per school for flushing water closets and urinals (after Nozaic and Freese, 2009) can be met by the all yields from the boreholes situated in schools' premises. The available surplus can be utilised for irrigating of sports fields and/ or gardens. In the long run, over the life-cycle span of the asset, installing a solar-powered system works out cheaper although the initial capital expenditure is higher.

6. CONCLUSIONS AND FURTHER RESEARCH

6.1 CONCLUSIONS

The study investigated the quantity of groundwater that is available for withdrawal in the Johannesburg inner-city while attempting to suppress the high water table. A hydrogeological conceptual model of the Johannesburg inner-city was created using data from literature and boreholes drilled as part of the study.

This research aims to create a more specific understanding of the aquifer underlying the area in order to develop a numerical model that will form a framework that will guide the development and monitoring of groundwater resources within the city. The importance of this research is that it is site-specific and is focused on catchment scale, which enables the city to make decisions on the infrastructural design requirements that are available for the amounts of groundwater available and inform drought response plans.

Literature surveys and field work were carried out to determine the specific geology of the area together with the in-situ water levels. This data was then used to develop a conceptual model, which was in turn an input into the FEA-based numerical model that sought to predict the behaviour of the aquifer under different pumpage scenarios. The field work entailed drilling of nine boreholes and then conducting pumping tests and water chemistry analysis.

The study site is mainly characterised by confined aquifers made up of different lithologies tri-divided into a north, central and a south third. The three thirds comprise the fractures that define the origin point of a fault system that makes up the Johannesburg graben valley. There is as much as 2.47 billion litres of groundwater available in the inner-city, as a long term total yield potential. This addresses the concern of whether the water is sufficient, and makes investment into groundwater reclamation for property owners viable. The study found that there is as much as 56 million litres that can be safely withdrawn from the aquifer as an annual yield. This ‘safe abstraction’ would result in an average drop of 2.3m in the water table level in the area per annum, resulting in the proportion of buildings experiencing occasional to regular flooding reduced from the current 60% to only 30%. Static water level measurements in current situation (no pumping scenario) show that there is an average recharge of about 0.19m across the area, indicating significant water services infrastructure leakages. The simulation scenario of the current situation assumes no abstraction because most buildings are pumping water that is decanting and have not drilled boreholes; and thus are redirecting the flow to protect their properties from flooding.

For South African Metropolitan Cities such as the City of Johannesburg, which rely on a water board for the extraction and supply of bulk water, the amount of groundwater that is available makes for a minute portion (0.2%) of the water demand supplied by the bulk infrastructure network. As a result, building a new bulk infrastructure specifically to connect the supplementary groundwater resource does not make economic sense. Therefore, the establishment of a groundwater resource is more prudently viewed as a complementary resource to build resilience into the system and mitigate against the increasing risk of water shortages posed by climate change related impacts. The number of boreholes was limited by the budget available and the locations of such boreholes within the area were dictated by access of space for drilling rigs as well as the security of those public spaces, once boreholes are equipped and operational.

6.2 FURTHER RESEARCH

More work needs to be done in the following areas, to solidify the knowledge base acquired:

- Further development and continuous calibration of the numerical model is required when the boreholes are in operation. Frequent water level measurements to be done after boreholes have been commissioned for operation so that calibration under pumping conditions happens in order to reach higher scenario prediction confidence under the operational conditions. The continued calibration should also consider data from other future operational private boreholes that can be accessed in order to account for number of boreholes was limited by the budget available and the locations of such boreholes within the area were dictated by access of space for drilling rigs as well as the security of those public spaces.
- Measuring and monitoring of seepage into the basements of buildings to further fine-tune the model calibration and assess the effectiveness of pumping the boreholes.
- Further testing of the water chemistry so as to verify current results and be able to develop drought response plans that are practical.
- Assess the risk of subsidence with the decreasing water table levels.
- Investigation into the groundwater-surface interaction and how extreme withdrawals would impact on the rivers originating from this area. Even though it was not explored in detail in the scope of this research, the general impression is that the water movement in this catchment is predominantly from groundwater system feeding into the rivers (i.e. gaining streams).

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APPENDIX A

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City of Johannesburg
Environment and Infrastructure Services Department

QUESTIONNAIRE: GROUNDWATER SEEPAGE OCCURENCE

You are hereby requested to kindly complete the questionnaire below which will assist the City of Johannesburg in its investigation into the occurrence of groundwater seepage in the inner-City and surrounding areas. An investigational project aimed at finding a sustainable solution to the problem has been commissioned and in progress.

For more information required about the project please contact the project manager, at 011 587 4208/9.

Name of company		
Address:		
Contact Person		
Contact details	**Email:**	**Number:**

Please complete the following questionnaire with specific regard to the above enquiry, by placing a CROSS **X** in the appropriate box.

		YES	NO
1.	Have you observed any occurrences of groundwater seepage inside and/or around the buildings/ structure that you are managing?	☐	☐
2.	Are you currently experiencing groundwater seepage? If yes, how recent are these occurrences and how severe are/ were they? ____	☐	☐
3.	Were there in-depth research studies conducted to understand the problem?	☐	☐
4.	Are there any research study reports or long term monitoring data sets available for sharing with the City?	☐	☐
5.	Are there any boreholes in the vicinity of your property?	☐	☐

City of Johannesburg
Environment and Infrastructure Services Department

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6.	Is/are the borehole/s mentioned above operational? If yes, please provide the physical conditions/ status (i.e. is the boreholes closed or still open for sampling) of the boreholes (you may provide photos) ____	☐	☐
7.	Are you currently pumping out water from any vicinity of your property to control the seepage water (e.g. borehole, basement, etc.)?	☐	☐
8.	Do you measure the amount of water that is pumped out? If yes, please provide quantity per day/ per week. ____	☐	☐

Additional Comments/ Information:

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Thank you for your help!

Please kindly scan and email responses to: Ondelaty@joburg.org.za

APPENDIX B

Table 3: Survey questionnaire feedback and reconnaissance study from the study area

No.	Site Name	Basement depth (mbgl)	Water level (mbgl)	Comments
1.	South Point Towers, 41 De Korte Street, Braamfontein	6	2.5	Two basement levels. Water seepage on the north-side walls constantly flowing through weep holes. Has a sump and submersible pump. Pumping onto the street and/or storm water inlet.
2.	Diamond House, 35 Melle street, Braamfontein	5	-	Single basement level. Sewerage pipes leaking. Walls dry.
3.	91 De Korte Street, Braamfontein	6	-	Two basement levels. Storm water ingress into the wall.
4.	Corner De Beers and Jorissen, Braamfontein	5	-	Single basement level. Seepage had only started in the recent two months. There is a water servitude running on the side of the building, which is suspected to be leaking. Water flowing in through weep holes.
5.	FNB House, 2 Reserve Road, Braamfontein	12	-	Four basement levels with well-designed sub-surface drainage system. Walls dry. There is a sump of about 1.5m deep with a submersible pump below level 4 and is collecting and pumping up onto the surface to a nearby blocked storm water inlet on Biccard str. Run-off frequently floods De Korte street.
6.	Taylor Mansions, 142 Pritchard Street, Johannesburg	6	-	Two basement levels. Suspected sewerage pipes leakage based on smell of water.

No.	Site Name	Basement depth (mbgl)	Water level (mbgl)	Comments
7.	Landrost, 88 Plein Street, Johannesburg	12	11.4	Four basement levels. Properly designed sub-surface drainage system with French drain on level 4. Flooding of basement level 4 occurs when pump is not working. Using 50mm diameter pipe and thus pumpage rate estimated to be ±1.5 – 2.0 l/s.
8.	Frank & Hirsh, 352 Bree street, Johannesburg	12	10.5	Four basement levels. Evidence of groundwater seepage visible on walls.
9.	Platinum Place, Corner Van Beek and Staib Streets, New Doornofontein	3	-	Single basement level. Properly designed sub-surface drainage system with French drain perforated pipes. There is a 2m deep sump with two submersible pumps. Pumping directly into the sewer system.
10.	Atkinson, 28 Albert Street, Johannesburg	9	-	Three basement levels. No sump in place. It is not clear whether it is groundwater seepage. It is suspected that the problem might be a leaking fire hydrant situated on the ground level outside the building. It could also be storm water runoff during rain.
11.	60 Main Street, Marshalltown, Johannesburg	11	-	There are five basement levels, which are about 2.2m high. Clean and well-designed drainage. There are two submersible pumps. H_2S smell in the sump. Dew acidic and corrosive.

No.	Site Name	Basement depth (mbgl)	Water level (mbgl)	Comments
12.	81/85 Main Street, Marshalltown, Johannesburg CBD	14	-	There are two basement levels, each about 7m high. Periodical pumping. Dry at the time of site visit. Water seems to flow from top, no ingress from the side at the bottom. Wall footing dry. Ingress from Harrison street side. Weep hole on the wall at 8m from ground level. Flooding of lift shafts after a heavy rain pour reported.
13.	100 Main Street, Corner Rissik, Marshalltown, Johannesburg CBD	12	-	Three basement levels of about 4m high. There is a borehole 26m deep from the bottom of the basement. Borehole water has never reached cap, thus no over flows at 12 mbgl. Could not remove the cap to the side to inspect water level.
14.	15 Marshall Street, Marshalltown, Johannesburg	15		Three basement parking levels and a 6m high pump and storage tank house. Groundwater constantly pumped. The drainage channel is a face-brick wall fascia that hides the seepage and water damage on the main structural wall. Therefore, seepage could not be observed on the wall, only seen in the collecting sump.
15.	45 Commissioner Street, Marshalltown, Johannesburg	10	11	Two basement levels, 5m high each. Basement mostly dry with very little groundwater seepage observed in a channel against the wall in a small basement room at 11m on one side of the building. Looking in the

No.	Site Name	Basement depth (mbgl)	Water level (mbgl)	Comments
				sump, there is constant draining flow and pumpage. Thus, if a pump stopped working, flooding would occur.
16.	Lastras building, 105 Albertina Sisulu street, Johannesburg CBD	3	-	Single basement level. Municipal water seeping into the building from a nearby servitude that is leaking. No signs of water marks on the walls. Water filling the floor area, probably seeping through the floor slab joint.
17.	Chapel Court, 37/ 39 Plein Street, Johannesburg CBD	4	-	Single basement level. Leaking infrastructure. Possible groundwater that is seasonal as there are channels that drain water to a sump but currently dry at the time of visit. Basement shop walls and floor dry.
18.	Cavendish, 183 Jeppe Street, Johannesburg CBD	4	-	Single basement level made up of shops. Seepage reported to be observed only during rainy season. Probable storm water ingress instead of groundwater.
19.	Elgin, 84 Delvers Street, Johannesburg CBD	3	-	Single basement level. Rainwater seeping from the street through paving after original wall was broken to fit in electrical transformer. Before installation there was no water seepage.
20.	Wits RHI, 22 Esselen street, Hillbrow	-		No basement. Built in 1905. There is a 1m box channel running underneath building and is sitting on a shale rock that has continuous seepage of water. Seepage observed on ground level and channelled

No.	Site Name	Basement depth (mbgl)	Water level (mbgl)	Comments
				away from building into sewer. Building does not have concrete, but is directly on a rock foundation structure. Building is constantly damp along a “vein”. Internal sampling and testing showed that the water is not municipal supply.
21.	iThemba Labs, PDH Building, 1 Jan Smuts, Braamfontein	5	4.5	Two basement levels. 56m Borehole on site. Workshop in basement has sump and is constantly pumping water out into a storm water drain, otherwise lift shafts and basement flooding occurs.
22.	45 Main street, Johannesburg	6	6	Two basement levels. There are no channels along the wall, water is collected and pumped out at the emerging point. Sump located directly at source and pumping directly into the sewer pipes. Water seepage on eastern side wall.
23.	55 Marshall, Johannesburg	14	4	Six basement levels. Slight seepage observed on the North West corner. Basement level 1 dry; water seepage starts at bottom of B2 and is present at all basements below that up to B6.
24.	Living@Rissik, 81 Rissik Street, Johannesburg	6	6	Two basement levels. Seepage observed at the bottom of lift shafts. Lift shafts become flooded when not pumping. Was purifying the water and using it for laundry. Pumping from sump to a Jojo tank.

No.	Site Name	Basement depth (mbgl)	Water level (mbgl)	Comments
25.	120 End Street, Doornfontein, Johannesburg	15	14	Four Basement levels. At bottom of level 4 seepage is observed. Pipes extruding from the base of wall collect water towards the centre into a 1.2m deep sump where there is a continuous dripping of water and automated submersible pump. Looks like the floor slab is leaking and allows seepage as the walls are dry. Channel collectors next to wall also dry.
26.	Greatermans, 220 Commissioner street, Johannesburg	3	-	Single basement level. Drainage channels relatively dry. Water seeping through wall and flooding floor but not enough to sample. Sump reportedly not working for a while and thus water has been stagnant for some time by the look of things.
27.	The Mark, 32 O'Riley Street, Berea	5	-	Reported to experience seepage during rainy season. Dry at the time of visit.
28.	Carlton Centre, 44 Kruis Street, Johannesburg	18	18	Six basement levels. Well-sealed building with no water marks and no seepage visible on the walls. Constantly pumping from the sump at the bottom of the basement. Reported that lift shafts flood when not pumping. There is a natural spring discharge point at the bottom of basement level 6. Pumping out at an average of 12 m^3 per day from the sump which has a network of collector pipes.

No.	Site Name	Basement depth (mbgl)	Water level (mbgl)	Comments
29.	Maxwell Hall, 96 Small street, Johannesburg	6	-	Two basement levels. No water seepage.
30.	Smitshof Court, 1 Hospital Street, Hillbrow	3	-	Single basement level. Leaking infrastructure meters. Signs of possible groundwater seepage, but for sampling purposes, water would be mixed with municipal water.