GROUNDWATER YIELD-RELIABILITY ANALYSIS AND OPERATING RULES FOR DATA CONSTRAINED RURAL AREAS IN SOUTH AFRICA

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by

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EXECUTIVE SUMMARY

BACKGROUND

Water supply systems that obtain water from groundwater aquifers require operating rules/strategies to regulate the competing water uses, ensure beneficial use of water and also account for groundwater reserve. Management strategies are also required to address the unique characteristics and roles of groundwater. Groundwater yield-reliability analysis is required when deriving operating rules. Operating rules provide statements on water to be allocated from a given resource at a given time. Most studies do not incorporate the reliability of groundwater supply in their analyses. This shows that there is lack of information on the level of reliability/assurance of groundwater supply in most groundwater operating rules/strategies.

RATIONALE

Since groundwater plays a crucial role in community water supply in most rural areas of South Africa, its optimal operation and management in such areas is essential. The National Groundwater Strategy (NGS) has been developed in South Africa to ensure that groundwater is an integral part of water resources planning across all sectors (DWA, 2010). To achieve this, groundwater yield-reliability analysis needs to be conducted to verify its assurance of supply. Lack of long-term groundwater yield data in most rural areas of South Africa hinders the development of groundwater operating rules and implementation of the NGS. Groundwater operating rules for such rural areas, which form the target of this study, can be developed by assessing the groundwater resource availability through alternative methods implemented in this study.

OBJECTIVES

- To review literature on existing methods for yield-reliability analysis and deriving operating rules
- To select and delineate a water scarce rural area as a groundwater resource unit (GRU)
- To assess groundwater resources for the GRU using groundwater balance
- To perform storage-reliability analysis and derive groundwater supply operating rules for the case study village

- To generalise groundwater operating rules for use in rural areas located in hydrogeologically similar environment

METHODOLOGY

Groundwater resource unit (GRU) for the study area was delineated to provide the basis for computing groundwater storage from groundwater balance equation. Hydrogeological conceptual model was developed based on geologic cross-section to conceptualise the groundwater flow behaviour in the GRU. Due to lack of continuous long-term data on the components of groundwater balance equation, non-parametric regression (NPR) and system identification models were used to patch and/or extend data. Groundwater balance and Weibull plotting position methods were used in a groundwater storage-reliability analysis approach aimed at deriving groundwater operating rules. The approach followed involved the use of water user priority classification and water quality assessment in the development of groundwater operating rules. Groundwater quality assessment indicated the suitability of groundwater for use or the need for specific type of interventions before use.

RESULTS AND DISCUSSION

The results of groundwater storage-reliability analysis showed that relatively high and low storages are associated with low and high reliability due to the fact that high storages result from heavy rainfall events, which rarely occur as compared to normal rainfall events. Low and high storages are also associated with high and low risks of failure, respectively. Operating rule curves showed that minimum storages required to meet low demand of 101 l/c/d (D_1) for 2015 was 20% while 30% was required to meet high demand of 189 l/c/d (D_2) for the years 2020 and 2030, respectively. Twenty five percent was required to meet D_2 and D_1 for the years 2015 and 2020, respectively. Estimated maximum supply from 40, 60, 80 and 100% of full groundwater reservoir storage levels (GRSLs) showed that daily available supply ranges exceed water requirements, and hence groundwater is potentially available for other uses such as subsistence farming and construction industry such as brick making and building. This confirmed that proper development of groundwater resources will contribute to reduction of poverty and ensure sustainability of livelihoods in Siloam Village.

Assesment of groundwater suitability for domestic use showed that turbidity and Electrical Conductivity (EC) values, fluoride, magnesium, calcium, sodium and phosphates were higher than the guidelines for domestic use in most boreholes. Turbidity and fluoride had the most significant potential health effects as they were linked to microbiological contamination of groundwater and mottled teeth (fluorosis) in the study area, respectively. Having recognised the impacts of excessive fluoride on human health in the study area, a number of studies on defluoridation have been initiated by University of Venda research groups using Siloam Village as a test site.

CONCLUSIONS

Derived operating rule curves show that groundwater has the potential to supply low domestic water demand from a minimum GRSL of 20% in 2015. This is projected to increase to a minimum GRSL of 25 and 30% in 2020 and 2030, respectively. Operating rules show that high domestic water demand can be met from a minimum GRSL of 25% in 2015, and 30% in 2020 and 2030. Estimated maximum supply from groundwater showed that groundwater has the potential to be used as a sustainable source of supply that contributes to poverty reduction and ensures sustainability of livelihoods in Siloam Village. Treatment of groundwater aimed at reducing fluoride concentrations and turbidity (providing conducive environment for microbial organisms) is crucial if groundwater is to be considered as a primary source of water supply and should therefore be part of the operating rules for the study area. Groundwater operating rules were generalised by summarising the procedure followed in the development of the operating rules in Siloam Village to allow their application in other areas located in hydrogeologically similar environments (crystalline basement aquifers). Applications in other hydrogeologically different environments (coastal or karst aquifers, for example) will possibly require prior testing and modification of the procedure.

RECOMMENDATIONS

Practical implementation of the operating rules would require installation of appropriate water supply and monitoring infrastructure. Monitoring and production boreholes as well as equipment to monitor groundwater levels is required to ensure practical implementation of the derived operating rules. Continuous monitoring of components of the groundwater balance, detailed geophysical investigation, borehole logging through drilling of new boreholes and pump testing should be carried out to enhance the hydrogeological conceptual model for the study area and future updating of the developed operating rules. The quality of groundwater should also be monitored continuously to ensure suitability for domestic use or necessary interventions. Further testing and/or application of defluoridation methods that have been developed using Siloam Village as a test site is essential. This will aid in identification and development of a suitable defluoridation method which, would enhance supply of groundwater with minimal health problems.

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1 INTRODUCTION AND OBJECTIVES

1.1 Introduction

In contrast to its strategic role as essential resource to help achieve community development and poverty alleviation in the Southern African Development Community (SADC), groundwater has remained a poorly understood and managed resource (FAO, 2003). It is estimated that over 60% of community water supply in South Africa is from groundwater (DWAF, 2004a), making it a strategically important resource that requires optimal operation. The groundwater resource availability for drought conditions is 7 500 million m^3/annum and the present groundwater use of between 2 000 and 4 000 million m^3/annum, means that there is potential to considerably increase groundwater supplies in South Africa (DWA, 2010). Thus, groundwater can provide adequate water to rural areas for small-scale local use if they are operated optimally.

The National Groundwater Strategy (NGS) has been developed in South Africa to ensure that groundwater is an integral part of water resources planning across all sectors (DWA, 2010). The implementation of the strategy requires groundwater yield data, amongst other requirements, for water resources assessment and planning. There is lack of groundwater yield data in most boreholes in rural areas of South Africa since it is difficult and also expensive to measure. Thus, the NGS cannot be implemented in rural areas with no groundwater yield data. The groundwater operating rules for such rural areas, which are the target of this study, can only be developed by assessing the groundwater resource availability through alternative methods implemented in this study.

Most groundwater studies estimate sustainable yield of the aquifer but do not incorporate reliability. Examples of such studies include Van Tonder *et al.* (2000), Monirul and Kanungoe (2005), Uddameri and Honnungar (2007) and McDowell (2010). Reliability analysis is essential for ensuring the assurance of supply from specific yields. The only study that has incorporated the reliability of the estimated yield is that of Khan and Mawdsley (1988). The study was, however, focused on an unconfined aquifer environment and did not consider the groundwater reserve. Meyer (2002) developed guidelines for the monitoring and management of groundwater resources in rural water supply schemes. The guidelines indicated the strategy for the management of groundwater including different variables to be monitored. Dennis (2007) developed the South African Groundwater Decision Tool (SAGDT) designed to provide methods and tools to assist groundwater professionals and regulators in making informed decisions concerning groundwater use, management and protection, while taking into account the fact that groundwater forms part of integrated water resources management. The developed tool is data intensive and may not be implementable in remote rural areas, which lack such data. DWAF (2004b) and Ravenscroft and Murray (2004a, b) document the groundwater management strategy, a framework for groundwater management of community water supply and implementation of a rural groundwater management system, respectively. Though a number of tools have been developed to manage and protect groundwater in order to aid its incorporation into the National Water Resources Strategy (NWRS), there has been poor practical implementation of such strategies in typical rural areas of South Africa due to the problems highlighted above. It is therefore necessary to develop an easily implementable approach for such areas.

The current study performed groundwater storage-reliability analysis to aid in development of weekly groundwater operating rules taking into account the groundwater reserve. This is also crucial in rural areas wherein the typical rural water supply analysis unrealistically aggregates data into monthly or annual time steps and does not incorporate reliability as reported in Ndiritu *et al.* (2011a, b). This study will therefore facilitate the implementation of the NGS in rural areas of South Africa. The method to be developed will make it possible to integrate groundwater supply with other sources in areas with no groundwater yield data from pumping tests. This will assist in water resources planning and management as illustrated in DWA (2010).

1.2 Objectives

- To review literature on existing methods for yield-reliability analysis and deriving operating rules
- To select and delineate a water scarce rural area as a groundwater resource unit (GRU)
- To assess groundwater resources for the GRU using groundwater balance
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2 LITERATURE REVIEW

2.1 Groundwater yield analysis

The techniques for groundwater resource evaluation require an understanding of the concept of groundwater yield (Mahajan, 2008). Yield is defined as the amount of water that can be supplied from the reservoir during a specified interval of time (which may vary from a day to several years depending upon the size of the reservoir) (Sophocleous, 1998b). The concept of yield can be applied on several scales, which are borehole, aquifer and basin scales. If a single borehole is the focus of the study then a borehole yield needs to be determined, if the study targets an entire aquifer then an aquifer yield should be determined (Njanike, 2001) and if the unit of study is a basin then a basin yield should be determined. Borehole yield is the maximum pumping rate that can be supplied by a borehole without lowering the water level in the well below the pump-intake (Njanike, 2001). The term aquifer yield is defined as the maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in hydraulic head in the aquifer (Njanike, 2001; Mahajan, 2008, 2009). Basin yield is the maximum rate of withdrawal sustained by the complete hydrogeological groundwater basin without causing an unacceptable decline in hydraulic head in the system or causing unacceptable changes to any other component of the hydrologic cycle in the basin (Sophocleous, 1998a).

The need for groundwater resources management has resulted in a vigorous debate about the way in which the “capacity” of an aquifer to deliver water in a sustainable way should be defined and determined (Kalf and Woolley, 2005). The concepts of safe yield and sustainable yield have been developed to address this. Safe yield is commonly defined as the attainment and maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge (Sophocleous, 1997). Sustainable yield is the quantity of groundwater that can be pumped in the long term by considering the future generations and all components of the hydrologic system, not only groundwater but surface water as well (Sophocleous, 1998b). The concept of safe yield ignores the other components of discharge from the system, such as evapotranspiration or baseflow to streams and wetlands (Ökten and Yacigizil, 2005). Groundwater management policies based upon this parameter yield some unintended consequences, such as drying up of streams, springs and wetlands with the loss of ecosystems or contamination of groundwater by polluted streams (Ökten and Yacigizil, 2005). Thus, the management of groundwater resources in a basin under ideal conditions would require the use of the concept of sustainable yield, which allows adequate provision of water to sustain streams, springs, wetlands, and groundwater dependent ecosystems (Sophocleous, 2000).

Sustainable yield of a basin should be a compromised pumping rate, which can be sustained by groundwater recharge and will not cause any unacceptable environmental, economic, or social consequences (Zhou, 2009). Sophocleous (1997) reported that a quantitative methodology for estimation of sustainable yield had not yet been perfected and suggested that a suitable hydrologic basis for determining the magnitude of possible development would be quantification of the transition curve (from groundwater storage depletion to full reliance on induced recharge), coupled with a projected pattern of drawdown for the system under consideration. Sophocleous (2000) suggested that to ensure sustainability of aquifers, it is imperative that water withdrawal limits be established based on hydrologic principles of mass balance. Application of the hydrologic balance equation requires good scientific judgment, adequate hydrologic data, and careful analysis of the geology and hydrology of the particular area (Sophocleous, 1998b).

Kalf and Wooley (2005) derived the equation for estimating sustainable yield based on conservation of mass principles. Based on this, for an abstraction rate, P_s, sustainable yield volume prior to equilibrium is given by Equation 2.1.

$$P_s t_s = \left(\int_0^{t_s} I dt - \int_0^{t_s} O_r dt + S_s \right) \tag{2.1}$$

Where I is the inflow, O_r is the outflow, S_s is sustenance storage and t_s is the equilibrium time. The inflow (I) and outflow (O_r) integral terms are required since they include the sum of all inflows and outflows that vary over time up to equilibrium time (Kalf and Woolley, 2005). Beyond equilibrium, the sustainable yield is simply the sustainable inflow rate (I_s) minus the residual outflow (O_{rs}) rate:

$$P_s = I_s - O_{rs} \tag{2.2}$$

Zhang and Kennedy (2006) determined the sustainable yield of aquifers in urban areas of Beijing based on changes to the groundwater budget equation from virgin conditions. The components of the equation include sources of anthropogenic recharge, including leakage from water mains and sewer pipes, seepage from septic tanks, irrigation, gardening, artificial recharge and groundwater withdrawals. Yates *et al.* (2005) used the detailed analysis of water level trends and groundwater budgets, to estimate the sustainable yield of the Seaside basin.

The simplest way to derive an estimate for the sustainable yield of a borehole is to study the behaviour of drawdowns observed during a hydraulic test (also known as a pumping test) of the borehole, through an appropriate conceptual model (Van Tonder *et al.*, 2001). However, this gives a single value of sustainable yield which cannot be used for yield-reliability analysis, which requires long-term time series data.

2.2 Storage yield-reliability analysis

The reliability of a system is defined as the probability that a system will perform the required function for a specified period of time under stated conditions (Chow *et al.*, 1988). Reservoir reliability is an expression of the likelihood or probability of meeting a given demand or the percent time the given demand can be met (Wurbs, 1991). Various definitions of reliability can be formulated to serve the purpose of a particular study and for alternative time periods (percentage of days, weeks, months, years) (Wurbs, 1991). Reliability can also be expressed in volumetric or periodic basis. Periodic reliability is the ratio (or percentage) of the number of time units the reservoir is able to meet the target demand divided by the total number of time units in the simulation (McMahon *et al.*, 2007b) or the percentage of years when the declared yield can be supplied in full (Khan and Mawdsley, 1988). For example a reliability of 90% states that there will be shortages on average in 10 out of 100 years (Khan and Mawdsley, 1988). Volumetric reliability is the ratio of the volume of water supplied to the volume of water demanded for the study period (McMahon and Mein, 1978).

Storage yield reliability analysis is used to determine the volume of water that should be stored in order to provide a specified water demand with a stated reliability (Rugumayo, 2001). Yield-reliability analysis methods based on streamflow data have been addressed extensively in research literature. McMahon and Mein (1986), Votruba and Broza (1989), Wurbs (1993, 1996) and Nagy *et al.* (2002) provide general reviews of modelling techniques for analysing reservoir/river system yield and reliability (Wurbs, 2005). Such methods include extended deficit analysis (EDA), behaviour analysis, sequent peak algorithm (SPA), Vogel and Stedinger empirical (log-normal) method and Phien empirical (Gamma) method. McMahon *et al.* (2007a) gives a review of these methods including the comparison of their performance based on global streamflow data. Other methods used for yield-reliability analysis include the Gould-Dincer suite of techniques (normal, log-normal and Gamma).

Khan and Mawdsley (1988) developed a lumped model which can be used to estimate reliable yield for an unconfined aquifer. The approach incorporated a historic recharge sequence and some initial conditions of storage in the water balance equations to describe the changes in storage and hence drawdown with time in the aquifer given an assumed abstraction rate and recharge (Khan and Mawdsley, 1988). The developed model closely resembles the mass curve analysis model used for surface reservoir yield analysis. Thus, mass curve analysis is applicable for reliability analysis for groundwater reservoirs.

Introduction of the National Water Act (NWA) in 1998 and the recognition that South Africa (SA) is a water-scarce country have placed a new emphasis on groundwater and its associated integrated management (Dennis, 2007). In response to this a number of studies carried out after introduction of the NWA focus on addressing this either by developing and/or applying approaches for determination of sustainable quantity of groundwater (yield) and/or their levels of assurance. The current review gives examples of such studies.

DWAF (2004b) proposed a method, termed Aquifer Assurance Yield (AAY), as a means of including the supply assurance concept into the groundwater resource assessment. The AAY approach incorporates aspects of water balance principles as well as more detailed risk assessment, thereby allowing for reliability during drought, above average availability after major recharge events, and policy requirements. The proposed method was not tested in the study DWAF (2004b), due to the fact that it is data intensive for application on the national scale.

Wright and Xu (2000) explored the possibility of applying the water balance methodology to estimate sustainable quantity of groundwater that would ensure sustainable groundwater management in SA. The study noted that the quantity of utilisable groundwater within a region may be identified as neither entering nor leaving a geohydrological unit (i.e. may not be in a state of flux). Such groundwater could be considered as being held in storage. The study concluded that the robustness of applying the water balance approach to sustainable groundwater management needs to be tested in SA through application.

DWAF (2006) proposed a procedure that makes use of potential storage volumes together with parameters such as rainfall, recharge and baseflow to determine the annual volumes of groundwater available for utilisation on sustainable basis. The developed method is applicable on a national scale or at the scale of an individual aquifer; the difference lies in the input data required (DWAF, 2006). The method requires aquifer thickness and storage coefficient data, which are mostly available as default values at a national scale and are therefore not useful at a local scale. Conrad and der Voort (2000) developed a methodology to determine the sustainable utilisable potential of South African aquifers at a catchment scale taking into account the groundwater reserve. The methodology has been tested in areas (Atlantis, Zeerust and Beaufort West) where there are extensive groundwater data and can only be applied at a catchment scale. The catchment being defined by a surface water divide, which in some instances is not the same as an aquifer boundary, is a limitation of the method (Conrad and Van der Voort, 2000).

Witthüser *et al.* (2009a) proposed the Groundwater Resource Assessment 3 (GRA3) methodology for regional estimations of assured yields. The methodology links the Groundwater Resource Assessment 1 data set (borehole median yields and classes) with the Groundwater Resource Assessment 2 (which contains assurance of supply information) in order to produce a map or maps that would provide aquifer type, yield and assurance of supply information. The yields estimated by GRA3 method are based on mean annual recharge figures, which have a typical recurrence interval of 2 years and therefore translate to approximately 50% assurance of supply (depending on the underlying distribution) (Witthüser *et al.*, 2009a).

Recent studies in SA including Witthüser *et al.* (2009a,b), DWA (2010) and Murray *et al.* (2012) have indicated the necessity of including level of assurance of supply (reliability) of groundwater in groundwater resource assessments. This is because the practical usefulness of single, time-invariant estimate of the average safe or sustainable yield of an aquifer to water resources planning and allocation is questionable, especially in the arid and semi-arid areas of SA where rainfall is extremely variable. The Aquifer Assurance Yield Model (AAYM) and Aquifer Firm Yield Model (AFYM) have been developed in SA in an attempt to address this.

In order to present yields in an accessible manner to water-supply planners, the same concept used in surface-water resource assessments and dam or reservoir design were adapted and applied to groundwater within the AAYM and AFYM. AAYM provides assured yields similar to assurance levels given in surface-water reservoir design estimated by statistical analysis of long-term time-series data of inflow against reservoir/aquifer storage and can vary according to various design-demand criteria (Murray *et al.*, 2012). The risk is defined as the percentage of years when the assured yield may not be supplied in full. The model is a simple groundwater-balance model that reproduces storage dynamics based on variable volumes of inflow and outflow and provides groundwater yields at 100% assurance of supply. The software model is run in monthly time increments on a quaternary catchment scale whereby inflow and outflow parameters (such as recharge as a percentage of Mean Annual Precipitation, evapotranspiration, baseflow and threshold) have default values, or alternatively can be set according to the user. It provides a rough estimate of the catchment's groundwater potential. AAYM needs to be modified to consider also shallow, porous, unconfined aquifers (currently strictly not applicable) as well as the considerable time lag between recharge and discharge in aquifers (Witthüser *et al.*, 2009b).

Murray *et al.* (2012) used the AAYM and AFYM to identify and quantify groundwater-development options for the main Karoo basin in South Africa. Aquifer Firm Yield Model is a modification of the AAYM and provides historical firm yields and not assurances of supply (Murray *et al.*, 2012). The firm yield is defined as the maximum volume of water that can be guaranteed from a reservoir/aquifer during a critical dry period, which is often based on the lowest natural stream flow/recharge sequence on record (Murray *et al.*, 2012). The essential components of the lumped-box AFYM are provided in Figure 2.1.

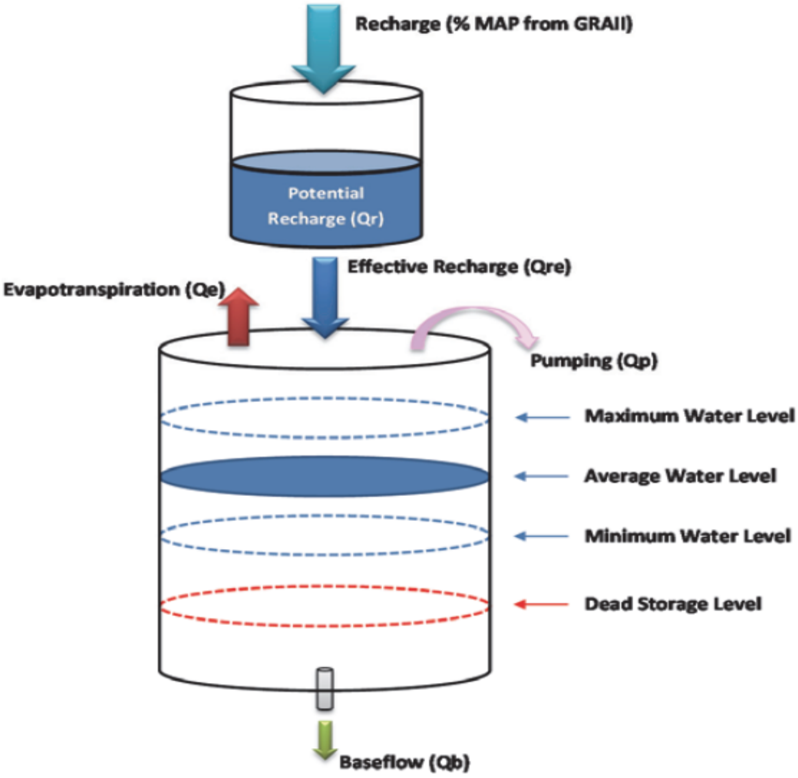


Figure 2.1: Essential components of the lumped-box AFYM (Murray *et al.*, 2012)

The above models are single-cell, lumped-parameter models and make use of critical management water level below which aquifer storage levels cannot be drawn down to provide estimates of the firm or assured yield of an aquifer (Murray *et al.*, 2012). This level

defines the volume of water held in aquifer storage that is available for abstraction and would take into account various physical, legal, societal or environmental constraints.
The aquifer yield models are only intended for use during the early planning stages of groundwater resource assessment studies where spatial and temporal hydrogeological information is scarce and perhaps several alternative schemes for increasing water supply are considered. Its limitations are related to both the assumptions on how well it simulates physical processes, which in this case is basic, being a box model, and the datasets from which the simulations are run (Murray *et al.*, 2012). Murray *et al.* (2012) suggested that users of this model should use site-specific data into the model whenever possible to account for the latter concern.

2.3 Groundwater operating rules/strategies

Operating rules are statements on how to schedule water from a given resource at a given time (season) (Johnson, 1993). Operating rules can assist in judging when the storage reservoirs can supply more than their minimum yield for a given risk (Ratnayka *et al.*, 2009). They are the policy instruments used to define operating conditions and procedures to implement when conditions are not ideal (Johnson, 1993). Reservoir operating procedures are a set of instructions, equations, tables or simply judgment decisions by which reservoir releases and diversions are determined based on current or forecasted state of the system (Guggino *et al*., 1983). The purpose of operating rules/policy is to distribute any necessary deviations from ideal/target conditions in a manner that satisfies mandated laws or regulations and/or that minimises the discomfort to all users in the system (Johnson, 1993; McMahon and Adeloye, 2005).

Basson *et al.* (1994) noted that it is generally not economically feasible to develop and operate water resources to meet the demand all the times especially in arid and semi-arid regions where the water resources are scarce and limited. Efficient operating rules are therefore required to improve on water supply reliability. In general, the state of the system may be described by reservoir levels, volumes, inflow, stages or flow at control points which act as independent variables to determine the reservoir release dependent variable (Guggino *et al.*, 1983).

Water supply systems that obtain water from groundwater reservoirs require operating rules/strategies to regulate the competing water uses and ensure the beneficial use of water and also account for groundwater reserve. Planning and operation of groundwater reservoirs require good knowledge of their characteristics and limitations of the aquifer, an estimate of their natural replenishment and outflows, as well as the determination of a programme for pumping (Harpaz and Schwarz, 1967). Management strategies are needed to address the unique characteristics and roles of groundwater, while at the same time preserving the concept of a common resource, in the context of both continuity within the hydrological cycle and national ownership of the resource (Pietersen, 2006).

In most groundwater studies simulation models are coupled with optimisation models to derive groundwater management strategies/operating rules. The same approaches are used in deriving operating rules for surface water reservoirs. Examples of such studies include Wurbs (1993), Lin *et al.* (2003), Sechi and Sulis (2009), among others. Simulation model basically provides solutions that obey the equations governing the relevant processes in the system while optimisation models identify an optimal management strategy from a set of feasible alternative strategies. Optimisation tools are utilised to facilitate optimal decision making in the planning, design and operation of especially large scale water resources systems (Datta and Hakrishna, 2004). The combination of simulation and optimisation produces an engineering design tool that can aid in the formulation of design criteria and assist decision makers in assessing the impacts of design trade-offs (Haddad and Mariño, 2010). Detailed reviews on the use of simulation and optimisation in groundwater management is presented in Gorelick (1983) and Das Gupta and Onta (1994).

There is no clear distinction between the terms operating rules, operating policies, management strategies or policies in most groundwater studies. For example, most of the studies that have been reviewed in the current report refer to operating rules as operating policies (for example, Shamir and Bear (1984)), operating management strategies (for example, Ökten and Yacigil (2005)) and management policies (for example, McPhee and Yeh (2004)). Studies such as Gallagher and Leach (2010) clearly referred to operating rules. Groundwater management, however, is much broader with operating rules as one of the components. The current review included studies on groundwater management strategies whose focus was on operating rules. It is important to note that in most studies operating rules, operating policies and operating strategies are synonymous terms and will be treated as such in this review.

Das and Datta (2001) presented a review on the state-of-the-art application of optimisation techniques in groundwater quality and quantity management. The study demonstrated the combined use of simulation and optimisation techniques in determining planning and management strategies for optimal development and operation of groundwater systems. The study reviewed the applications of mathematical programming techniques such as linear programming (LP), nonlinear programming, mixed-integer programming, optimal control theory-based mathematical programming, differential dynamic programming, stochastic programming, combinatorial optimisation and multiple objective programming for multipurpose management of groundwater quality and quantity. The current study has reviewed examples of studies that have applied the latter techniques for deriving groundwater operating rules. Examples of studies reviewed by Das and Datta (2001) that used such techniques to derive groundwater operating rules include Willis (1983), Willis and Liu (1984) and Hallaji and Yazicigil (1996). The studies have been summarised below.

Willis (1983) used LP to determine the optimal pumping scheme for three consecutive periods in order to meet agricultural water demands for an unconfined aquifer in the Yun Lin basin in Taiwan. Willis and Liu (1984) applied an optimisation model to the Yun Lin groundwater basin in southwestern Taiwan to generate optimal planning policies and a set of non-inferior solutions. The objectives of the optimisation model were to determine the trade-offs associated with additional groundwater development and agricultural demands. Hallaji and Yazicigil (1996) proposed six LP models for steady and transient states, and one quadratic optimisation model for steady state management of the coastal aquifer in southern Turkey. Water demand was one of the general constraints in the model.

Harpaz and Schwarz (1967) performed an optimisation analysis on a simplified single cell model representing an aquifer system for optimal operation of the aquifer. This was aimed at operating the aquifer as a water supply reservoir. The study presented four combinations of alternative plans representing two extreme climatic conditions. Shamir and Bear (1984) determined optimal annual operation of a coastal aquifer using multiple objective linear programming model based on a multi-cell model of the aquifer and a network representation of the hydraulic distribution system. The model provides a means for determining an operating policy for one season or one year in a coastal aquifer. It contains in the constraints a model of the physical systems: water balance in aquifer cells, mass balance of a conservative pollutant in aquifer cells, sea-water fresh water interface location in coastal cells and continuity equations for the hydraulic system.

Yazdanian and Peralta (1986) developed a method for designing a regional groundwater withdrawal strategy that maintains a set of optimal potentiometric surface elevation using the goal programming approach. The method was applied to the Grand Prairie region of Arkansans. The study concluded that the method was well suited for designing sustained yield strategies.

Das Gupta *et al.* (1996) noted that most of the earlier groundwater quantity management models (Aguado *et al.,* 1974; Dreizin and Haimes, 1977; Wanakule *et al*., 1986; Lindner *et al*., 1988; Peralta *et al.,* 1991) were applied to hypothetical conditions while their practical applications were limited to single-aquifer systems for short periods of time. Das Gupta *et al.* (1996) developed and applied an operational groundwater management model for pumping and recharge policy by maximising net relative benefit or minimising operation cost, subject to a specified allowable drawdown, minimum pumping requirement and maximum allowable recharge. The model was developed for the Bangkok, Phra, Pradaeng and Nakhon Luang aquifers in Bangkok. The study simulated the hydraulic response of a multi-aquifer system using the finite-difference alternating direction implicit scheme. Detailed information of the scheme is found in Das Gupta *et al.* (1992).

McPhee and Yeh (2004) used groundwater simulation and optimisation approach to construct a decision support system (DSS) for solving a groundwater management problem for the Upper San Pedro River Basin, located in southeastern Arizona. The approach used in the study was such that, once the algorithm identified a set of efficient solutions (alternatives), concepts borrowed from fuzzy set theory were applied to rank the alternatives and to assist decision makers in selecting a suitable policy among them, each of which was optimum with regard to its goal and the corresponding consequences. The results provided the payoff matrix that allows decision makers to know, given the then state of knowledge of the system and the simulation tools applied to the problem, the best and worst values of the objectives considered, and the trade-offs providing direction in terms of desirable and attainable management policies.

One of the components of the DSS, in the study by McPhee and Yeh (2004), was the management model which was aimed at defining sets of best groundwater pumping and recharge policies in a basin where groundwater was the main supply source. The management model incorporated operational sectors (defined by the spatial variability of the demand), effluents and return flow from the operational sectors and discharge or recycling of treated water at discharge facilities, which were considered when formulating the management objectives.

Ökten and Yacigizil (2005) developed a numerical groundwater flow model for the Sandy Complex aquifer in the Ergene River Basin, Thrace Region, Turkey. The model was used to develop groundwater pumping scenarios in order to predict the changes in the aquifer system under a set of different pumping conditions for a planning period of 30 years. The groundwater pumping scenarios were developed to determine the safe and sustainable yields and the limits of utilisation for the Sandy Complex aquifer. The study derived appropriate suite of management policies and plans were provided that promoted sustainable development of the aquifer system.

Gallagher and Leach (2010) developed a module of MODFLOW package called the Groundwater Operational Management Package (GWOMP) to improve the link between water resource planning objectives and the simulation of future groundwater system behaviour under different management schemes. The programme produces a detailed account of the extractive deficits recorded within management areas over the simulation period, as well as the history of trigger activation and operational decisions, which, when examined in association with the model simulated head and flow response under the operating rules, allows a robust statistical assessment to be made of the potential impacts on groundwater-dependent ecosystems and the reliability of water supply. The study further reported successful application of GWOMP in the water resource planning and operating plans for Pioneer Valley and Burnett basins in Queensland.

Pietersen (2006) used a multiple criteria decision analysis (MCDA) approach to identify critical alternative courses of action and to develop a decision-making framework for sustainable groundwater management. The study proposed a number of strategies for sustainable groundwater management in Namaqualand, South Africa. The study noted that the application of the tool in a participatory environment will require further refinement and adaptation (including further work related to sensitivity analysis). Pietersen (2006) study followed the methodology used in developing the decision model for groundwater in Namaqualand by Pietersen (2004).

Dennis (2007) developed the South African Groundwater Decision Tool (SAGDT) designed to provide methods and tools to assist groundwater professionals and regulators in making informed decisions concerning groundwater use, management and protection, while taking into account the fact that groundwater forms part of integrated water resources management. The SAGDT is a spatially-based software package which includes a geographic information system (GIS) interface, risk analysis interface that uses fuzzy logic based risk analysis to assist in decision making by systematically considering all possibilities, a third-party software such as a shape file editor, an interpolator, a georeference tool, a unit converter and a groundwater dictionary, a report generator and a scenario wizard.

The SAGDT evolved from the Groundwater Decision Tool (GDT) developed by the Water Research Commission (Dennis *et al*., 2002). The GDT application employs fuzzy logic for risk assessments in the following areas: groundwater sustainability, groundwater pollution, health and ecological environment. The developed tool is data intensive and may not be implementable in remote rural areas, which lack such data. The SAGDT allows problem solving at a regional scale or a local scale, depending on the problem (Dennis, 2007). The SAGDT was applied to real life scenarios using case studies on vulnerability (Fish River Lighthouse), waste site (Bloemfontein Suidstort), sustainability (De Hoop) and opencast mine (Van Tonder's Mine). The SAGDT relies heavily on the expertise of geohydrologists, assumptions and approximations of real world conditions. Together with the heterogeneities present in groundwater systems, it is impossible to guarantee the accuracy of the methodologies and the reader must take this into consideration (Dennis, 2007).

The reviewed studies have not incorporated the reliability of groundwater supply in their analyses. This shows lack of information on the level of assurance of groundwater in most groundwater operating rules/strategies.

3 GROUNDWATER RESOURCE UNIT (GRU) AND HYDROGEOLOGICAL CONCEPTUAL MODEL AND FOR THE STUDY AREA

3.1 GRU for the study area

The study area is Siloam Village, which falls under quaternary catchment A80A of the Nzhelele River Catchment in Limpopo Province of South Africa. The study area is found between 22°53'15.8" S and 22°54'5" S latitudes and 30°11'10.2" E and 30°11'23.5" E longitudes (Figure 3.1). The study area is dominated by human settlements and subsistence agriculture (Figure 3.2).

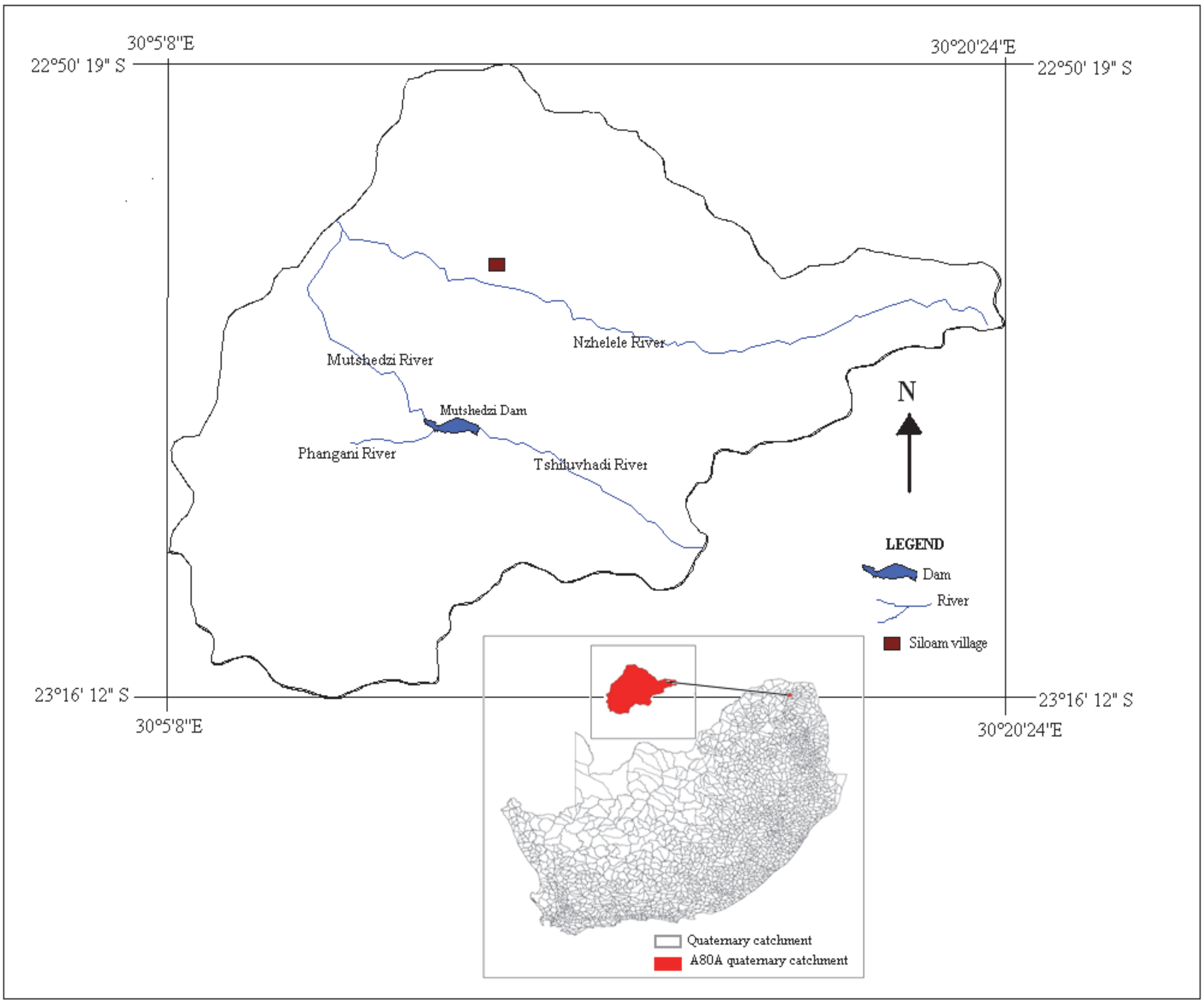


Figure 3.1: Location of Siloam Village in A80A quaternary catchment (Odiyo *et al.*, 2015)

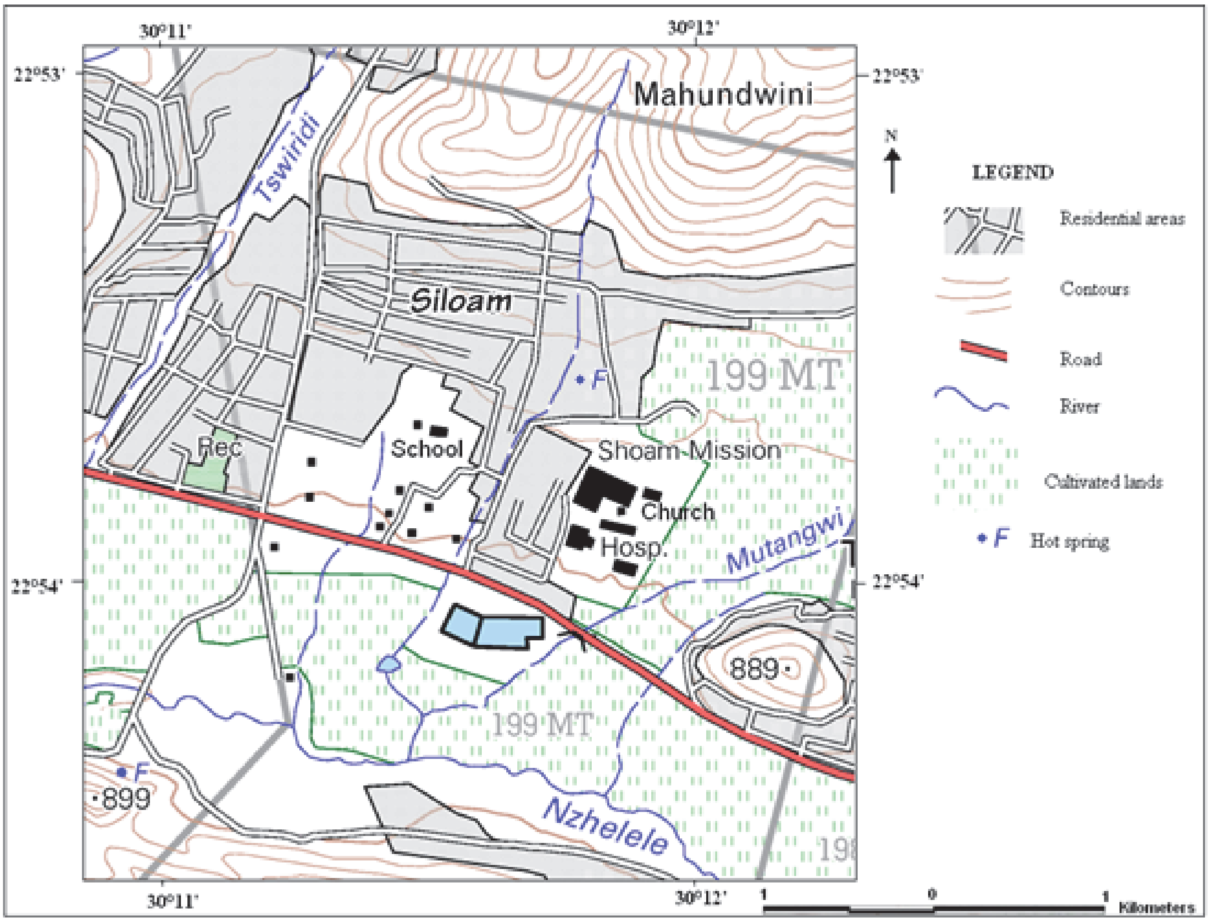


Figure 3.2: Topographical map of Siloam Village (Odiyo *et al.*, 2015)

Figure 3.3 shows GRU delineated from processed Landsat images and digital elevation models (DEMs). The upper boundary of the GRU can be assumed as a no-flow boundary. The mountain forms a groundwater divide at this boundary. Groundwater divide separates areas where water flows in one direction from areas where it flows in another. The concept of groundwater divide has been used for delineation of groundwater units in studies such as Sheets and Simonson (2006). Groundwater divides are frequently simulated as no-flow boundaries in groundwater flow models to limit the areal extent of the system being analysed (Reilly, 2001). The relationship between groundwater levels and topography (Figure 3.4) shows that topography controls groundwater levels in the study area and hence groundwater divide can be defined as a closed boundary. This is because in areas where topography controls groundwater levels, groundwater on each side of the divide moves away from the divide and no flow crosses the divide. Use of groundwater divides as boundaries can sometimes be justified without a sensitivity analysis if the only objective of simulation is to gain an understanding of the natural flow system in its unstressed condition (Franke *et al.*, 1987). Groundwater flow system for the study area is currently unstressed. Figure 3.4 has been plotted using once-off groundwater levels data for boreholes in Table 3.1 obtained from the National Groundwater Archives.

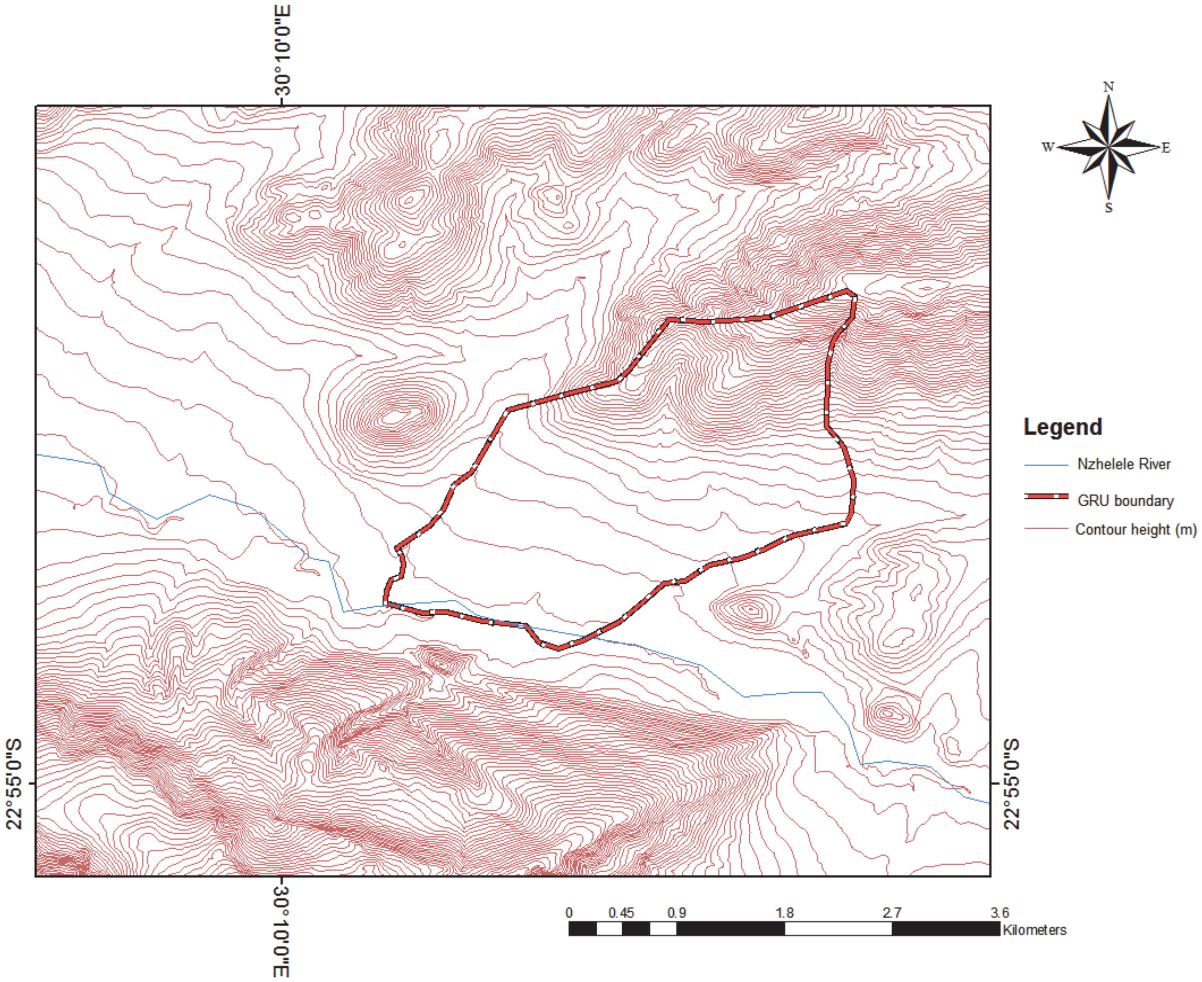


Figure 3.3: GRU and topography

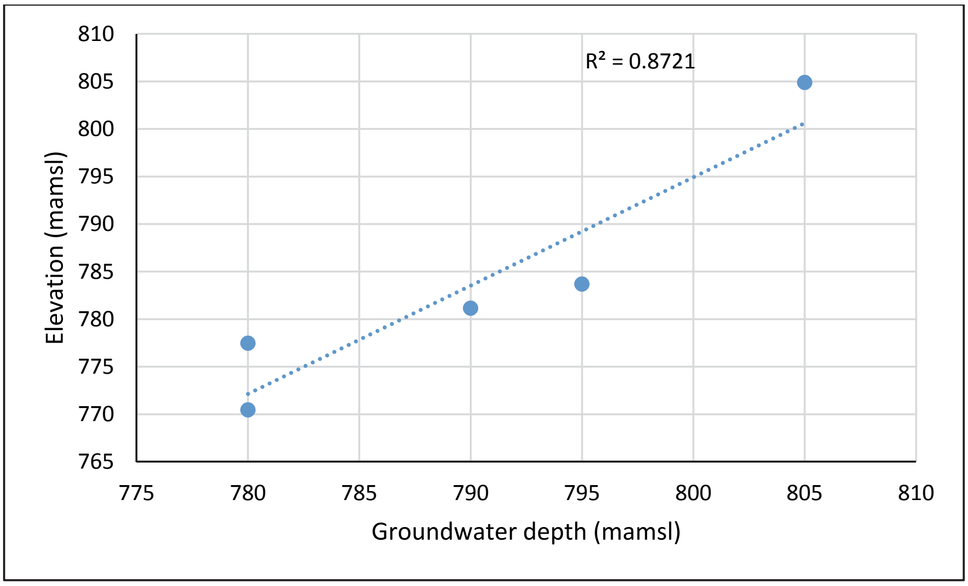


Figure 3.4: Relationship between groundwater levels and topography

Table 3.1: Topography and water level for boreholes

Borehole	Topography (mamsl)	Water level (m)	Water level elevation (mamsl)
H27-0138	805	0.12	804.88
2230CC221	795	11.31	783.69
2230CC222	790	8.85	781.15
H27-0168	780	2.54	777.46
H27-0051	780	9.54	770.46

Interpretation of magnetic data showed low magnetic anomalies/intensities (blue-green) colour (Figure 3.5) around the study area. This indicates that linear structures based on surface magnetic data are not highly pronounced and cannot be defined as no-flow boundaries. Surface magnetic data could therefore not be used in the delineation of the GRU. Thus, detailed geophysical investigations are still required to identify and verify the extent and depth of the linear structures. Earlier studies done in the Siloam Village (for example Nyabeze *et al.*, 2010; 2011a, b) focused on detailed geophysical investigations only along the Siloam hot spring, thus such data is not available for the rest of the Siloam Village. Landsat images and DEMs also showed linear structures on the surface which were used in the delineation of the rest of the GRU boundaries. Thus, these boundaries are open flow boundaries.

The lower boundary runs along Nzhelele River (Figure 3.3), which is a perennial river, and is thus, a flow boundary where interactions between surface water and groundwater will be estimated. The rest of the boundaries in Figure 3.3 follow non-perennial/ephemeral rivers. They therefore also constitute open flow boundaries. The inflows and outflows from these boundaries were estimated based on the methodology proposed by Singhal and Goyal (2011). The latter study proposed the use of GIS and water levels to estimate gradient (inflows and outflows) across the boundary. There are no groundwater levels for the study area. A8N0508 (Mandala) and A9N0009 (Tshidzivhe) were selected as representative boreholes and their groundwater levels adopted for use in estimating inflows and outflows across the Nzhelele and non-perennial/ephemeral rivers boundaries. These boreholes were selected based on comparable characteristics of their location with those at the river boundaries of Siloam Village GRU (Table 3.2). These characteristics include topography, geology, hydrogeology and mean annual precipitation. In addition, the borehole A8N0508 is in the same quaternary catchment as the GRU.

Table 3.2: Borehole and GRU river boundary characteristics

Feature	Nzhelele River boundary	A8N0508 (Mandala) borehole	Non-perennial rivers boundaries	A9N0009 (Tshidzivhe) borehole
Topography	780	810	800-900	920
Geology	Alluvium	Alluvium	Basalt/Arenite	Basalt/Arenite
Mean Annual Precipitation (mm)	300-400	300-400	300-400	409
Hydrogeology	Class b3 (Fractured aquifers, yield ranging from 0.5-2 l/s)			

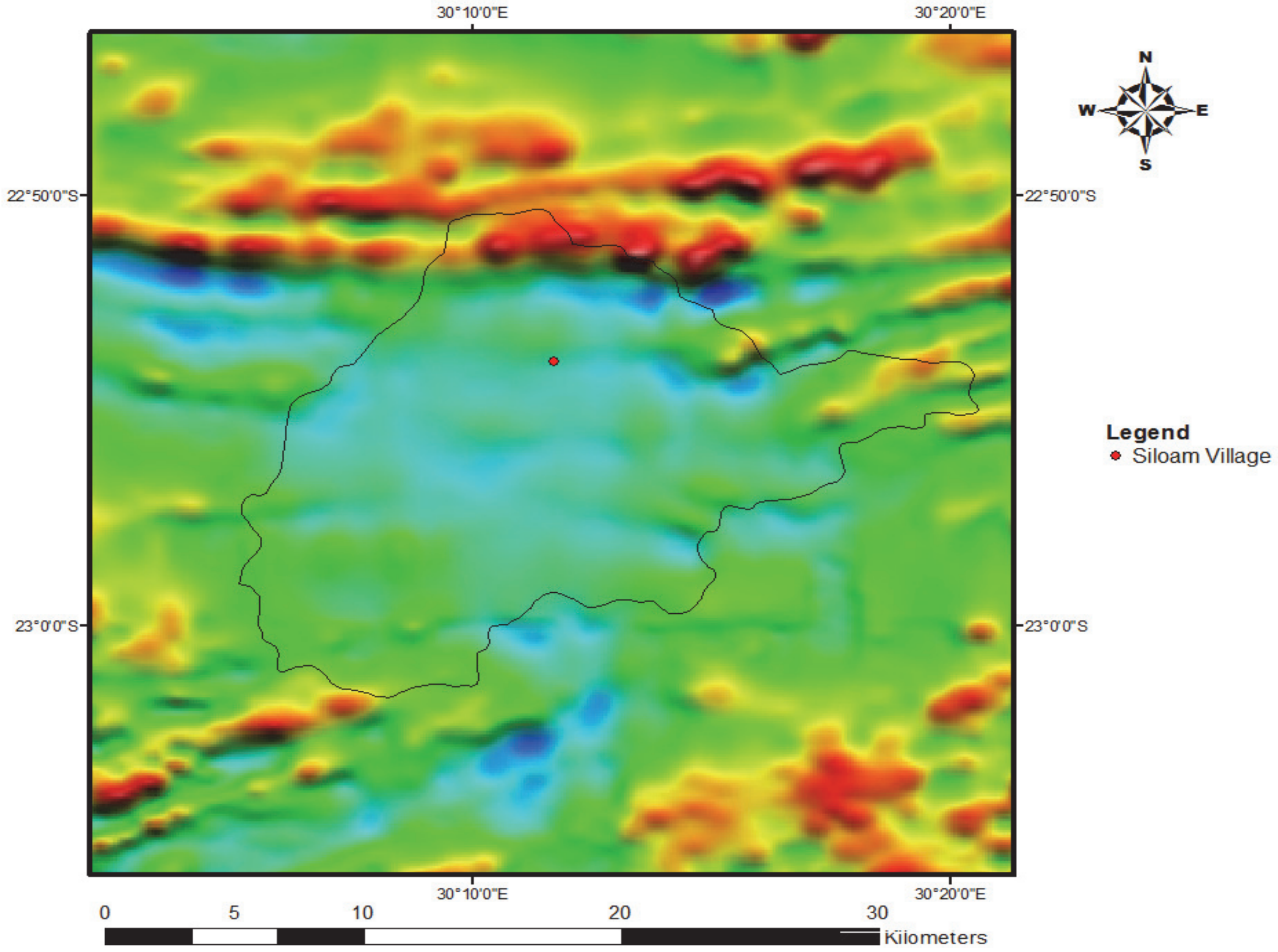


Figure 3.5: Magnetic map for Siloam

3.2 Hydrogeological conceptual model

A hydrogeological conceptual model is a pictorial presentation of the groundwater flow system incorporating all available geological and hydrogeological data into a block diagram or geological cross-section (Anderson and Woessner, 1992). Construction of a hydrogeological conceptual model involves defining geological and hydrological frameworks of the study area. Data for the geological framework is typically obtained from geological maps, borehole logs, geophysics and additional field mapping (Wilson, 2005). Construction of the geological framework then allows the hydrological framework to be defined involving the following: (a) identifying the boundaries of the hydrological system, (b) defining hydrostratigraphic units, (c) preparing a water budget, and (d) defining the flow system (Sefelnasr, 2007).

Building a conceptual model is an iterative process that can identify gaps in the data, which can be improved with further data gathering (Jackson, 2007). Thus, it is expected that there will be continuous updating of the hydrogeological conceptual model of the study area as more data becomes available.

3.2.1 Geology

- **Regional geology**

The study area falls within the younger covers of the Limpopo Mobile Belt (LMB). The LMB (Figure 3.6) of southern Africa is an extensive high-grade terrain that can be subdivided into three lithologically and structurally distinct zones, which are the northern marginal zone (NMZ), central marginal zone (CMZ) and SMZ. The LMB was formed as a result of a collision between the Kaapvaal craton (KC) and the Zimbabwe craton (ZC). The 250 km, ENE-WNW trending LMB is thought to represent a Himalayan-style collision event between the KC and ZC in the north (Bejaichund *et al.*, 2009). The oblique nature of this collision is believed to have initiated or re-activated major transcurrent fault systems, resulting in important structures such as the Thabazimbi-Murchison lineament, which prepared the craton for the development (2600-2100 million years ago) of the Transvaal and Griqualand West basins (Singh *et al.*, 2009).

Soutpansberg depositional basin was formed between two major crustal blocks, (e.g. the Kaapvaal craton in the south and the Limpopo Belt in the north) as an east-west trending asymmetrical rift or half-graben along the Palala Shear Belt (Brandl, 2003). Its rocks rest unconformably on gneisses of the Limpopo Belt and Bandelierkop Complex. The Bumby *et al.* (2002) suggested that the Soutpansberg Group may have been related to a half-graben bound to the south by a northwards-dipping normal fault, perhaps associated with orogenic collapse of the Limpopo Belt. The major faults which trend ENE through the Soutpansberg region almost certainly represent reactivated basement fractures (Mason, 1973).

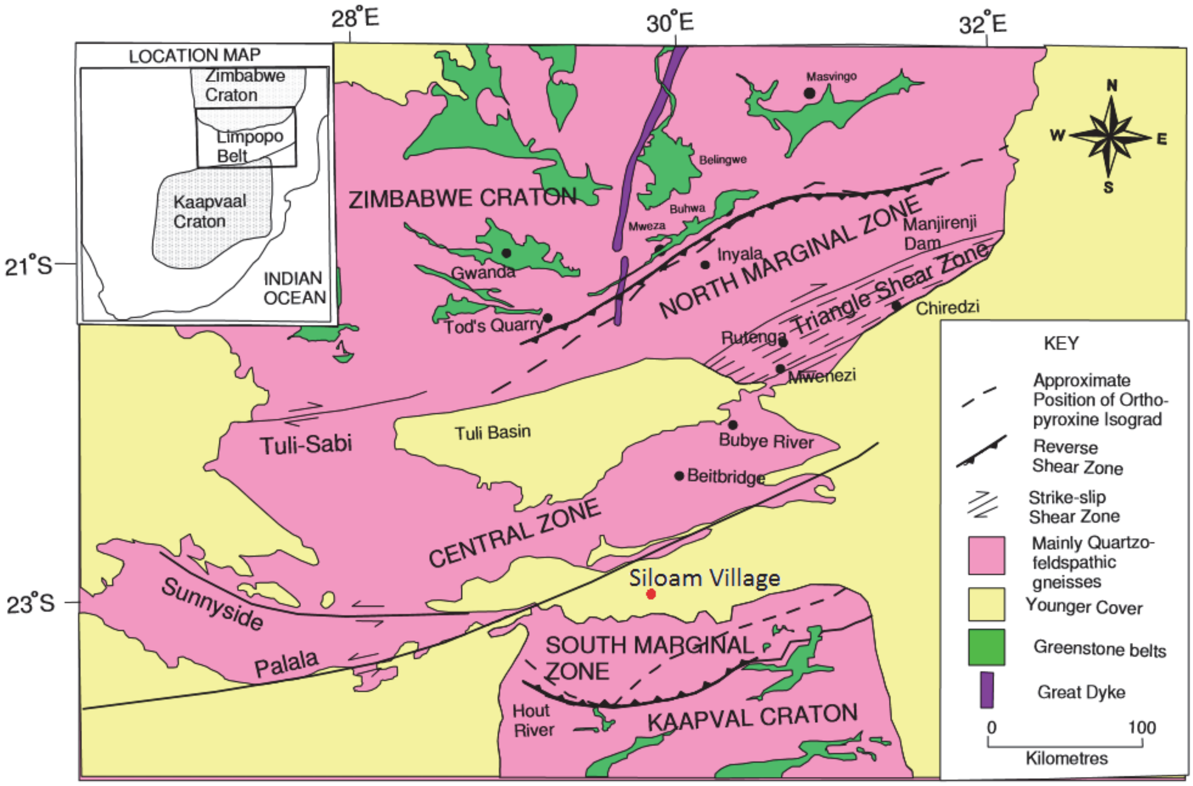


Figure 3.6: Simplified map of LMB (Chinoda *et al.*, 2009)

- **Local geology**

The study area falls within the severely faulted Soutpansberg Group of the Mokolian age (Figure 3.7. The Soutpansberg Group emerges as a large east-west trending mountain range (escarpment) from the Kruger National Park in the east to Vivo in the west. Dykes and sills of diabase are plentiful in the Soutpansberg rocks (Brandl, 2003). It has 7 formations which are Tshifhefhe, Sibasa Basalt, Fundudzi, Nzhelele, Wylliespoort, Stayt and Mabalingwe (Figure 3.8). The Sibasa Basalt, Fundudzi and Nzhelele formations are the ones that are present in the study area.

Sibasa formation consists predominantly of lava with minor intercalations of sedimentary and tuffaceous rocks (Brandl, 1981). The volcanic rocks comprise of repetitive sequence of erupted basalt (Barker *et al.*, 2006). Sedimentary rocks, which include shale, quartzite and conglomerate, generally tend to be more persistent along strike in the upper part of the succession (Brandl, 1981). Argilaceous rocks, interbedded with sandstone, represented by brownish or purple micaceous sandy shale, grey or dark-red shale and thinly laminated dark grey siltstones dominate the Fundudzi Formation (Brandl, 1981). The Nzhelele formation, which is the uppermost unit of the Soutpansberg Group, consists of a volcanic assemblage at the base followed by red argillaceous and arenaceous sediments together with several thin, though fairly consistent layers of pyroclasic rocks (Brandl, 1981; Barker *et al.*, 2006). Siloam fault trends from west-north-west to north-west and is estimated to have a vertical displacement of 1500 m. Large, fairly thick alluvial deposits are found along Nzhelele River (Brandl, 1981).

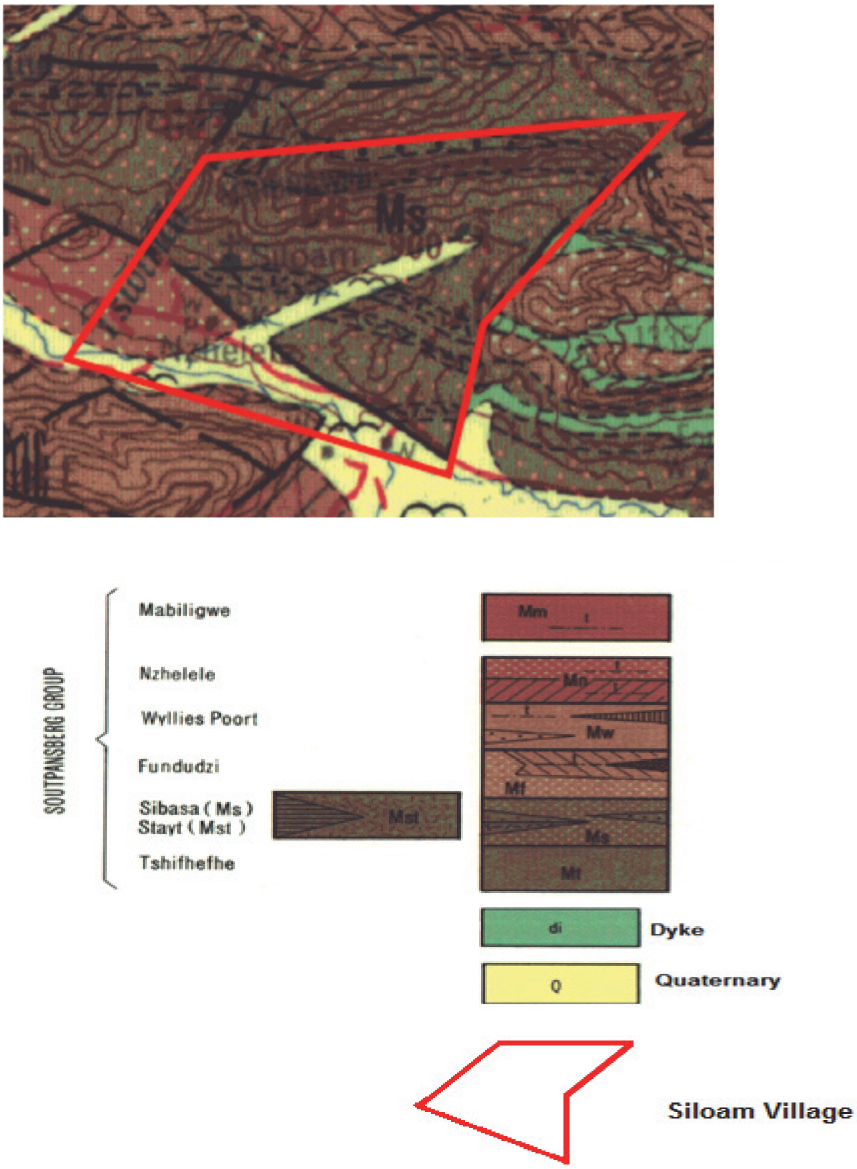


Figure 3.7: Local geology

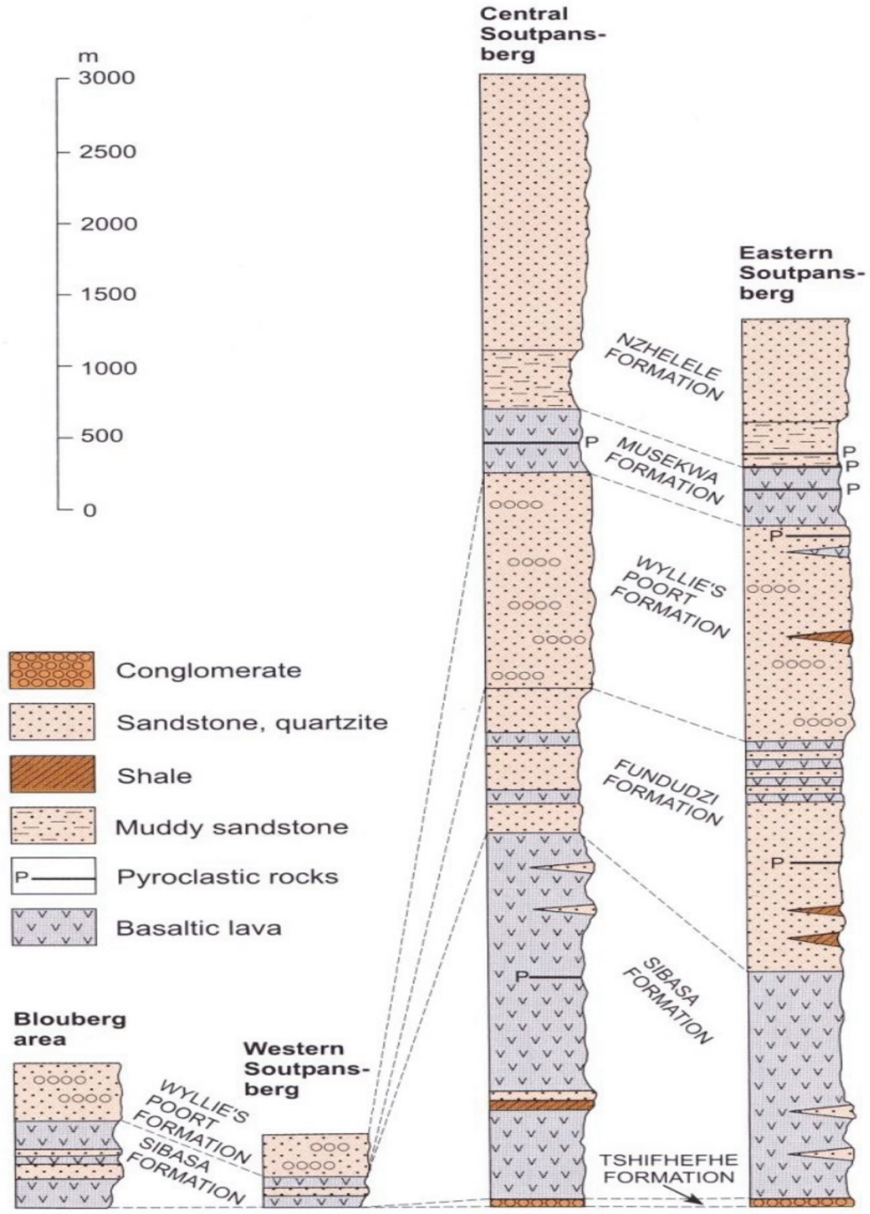


Figure 3.8: Stratigraphy of the Soutpansberg Group in the western, central and eastern Soutpansberg areas, and Blouberg area (Barker *et al.*, 2006)

3.2.2 Geological cross-section and hydrogeological conceptual model

Figure 3.9 shows cross-section line C-D from which geologic cross-section was based. The cross-section line was drawn on the map showing geologic formations of the study area. This map has been extracted from the 1:250000 geologic map series for 2230 Messina. The cross-section line C-D was selected because it is perpendicular to major geological features/structures, and it cuts across the study area and the Nzhelele River. The geologic formations include Sibasa Basalt, Fundudzi and Nzhelele formations and have been described in sub-section 3.2.1. Figure 3.10 shows the geological cross-section C-D. A closer observation on geological map shows that bedding dip to the north direction with 30, 27 and 20 degrees orientation (Figure 3.9).

The study area falls within the crystalline basement aquifers of the Limpopo Province. Crystalline basement rocks are usually semi-confined (fractured bedrock) with water-table aquifers (the matrix-regolith) situated on top of them (Holland, 2011). Wright (1992) stated that basement aquifers have low permeability and the main groundwater flow systems are relatively localised. In basement aquifers, groundwater occurs in secondary porosity/fractures caused by weathering and fracturing (Adams *et al.*, 2004). The main flow paths in fractured rocks are along joints, fractures, shear zones, faults and other discontinuities (Singhal and Gupta, 2010). Groundwater flow in fractured basement aquifers is only possible along preferred pathways due to heterogeneity in their hydraulic properties (for example, porosity and permeability) (Mohammed *et al.*, 2015). Fractures serve as primary sources that store and allow movement of water in hard rock areas (Sharma and Baranwal, 2005). Since the study area falls within severely fractured Soutpansberg Group, groundwater is likely to be stored in fractures and is expected to flow through preferential pathways. Thus, groundwater flow mostly occurs through interconnected fractures.

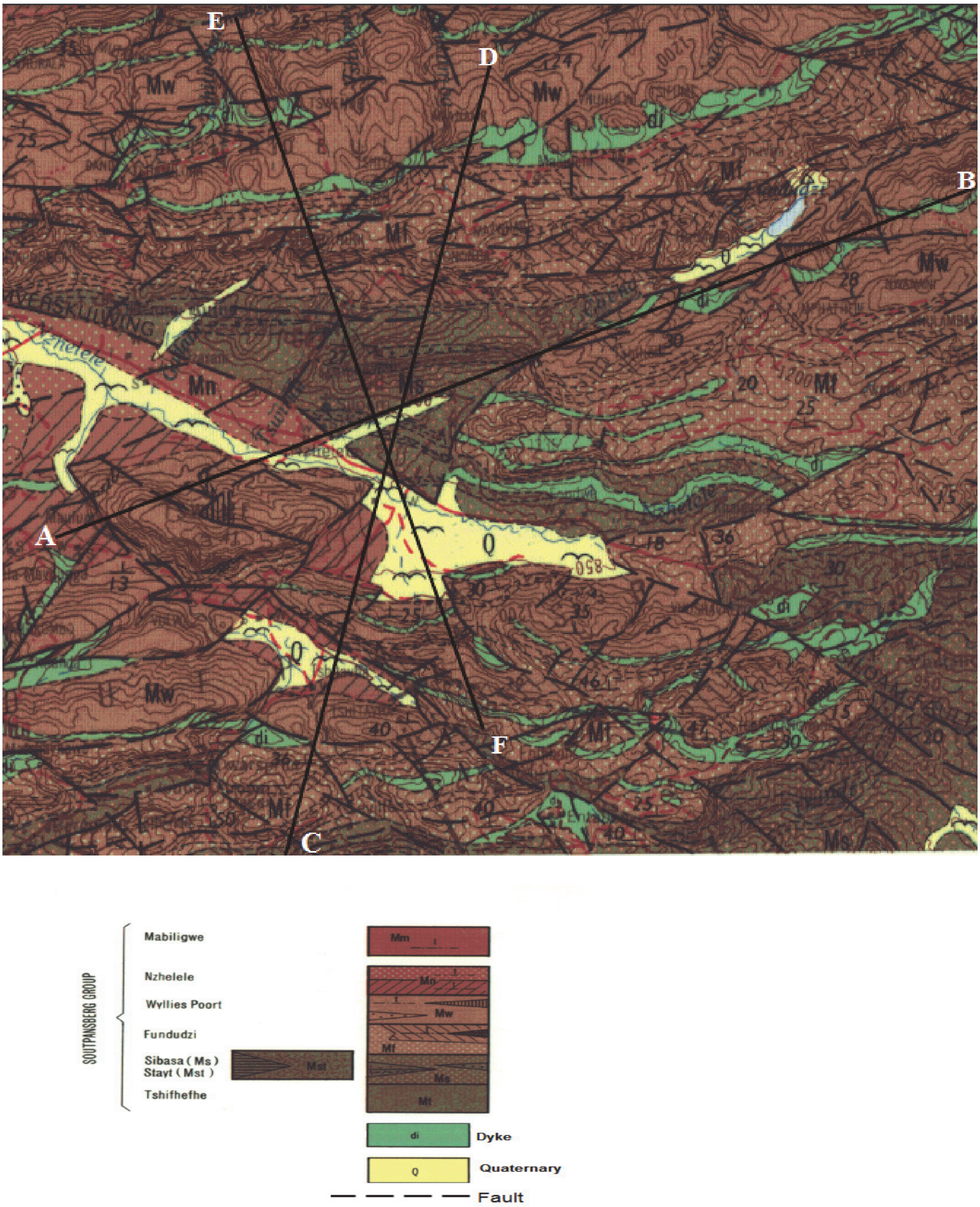


Figure 3.9: Cross-section lines CD in the geological map

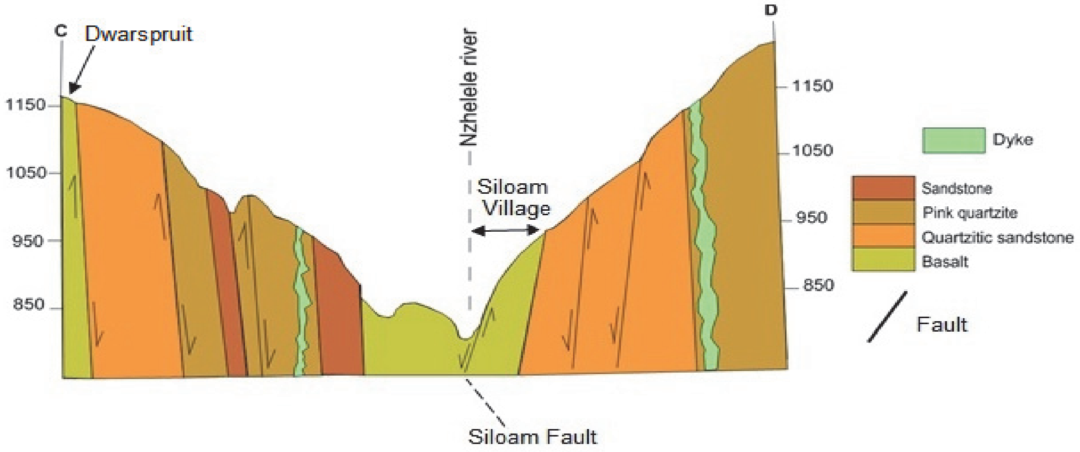


Figure 3.10: Geologic cross-section C-D

Siloam fault which cuts across the study area plays a significant role in controlling groundwater flow and storage. Faults create linear zones of high secondary porosity which may act as preferred channels of groundwater flow (Singhal and Gupta, 2010). Fractures exposed to the surface can also create preferential flow paths, which short circuit the path to the water table (Holland, 2011). Thus, the fractures visible on the geological map together with Siloam fault create preferential flow paths into the aquifer. It is important to note that the depth and thickness of the fractures is unknown and hence knowledge of the extent to which they influence groundwater flow is limited. Dippenaar *et al.* (2009) reported that in fractured aquifers, flow does not inherently occur in the direction of the fracture alone but it may be restricted to distinct channels within the fracture plane.

Diabase dykes are present within the vicinity of the study area (Figure 3.9). Dykes are prominent landform features that concentrate groundwater flow and storage (Kebede, 2013). They can act either as good conductors of, or as barriers to, groundwater flow depending on the intensity of fracturing associated with the dykes, and their trends in relation to the hydraulic gradient (Babikera and Gudmundsson, 2004). Morel and Wikramaratna (1982) reported that if dykes contain more fractures than the host basement rock, they improve the potential yield of the aquifer. A study by Holland (2012) showed that dykes were important water-bearing features in the Limpopo Plateau. Dykes are also likely to serve as water-bearing features in the study area. The dykes in the geological map have no values. Thus, it is not possible to know how deep they are unless exploration drilling is carried out where core samples can be taken for hydraulic properties testing *in situ* or in the laboratory, which is not the scope of the current study.

In the geological map (Figure 3.9), bedding planes, main fractures, dykes and the river trend east-west (E-W). Since groundwater is expected to flow through the fractures, the groundwater flow is likely to be from E-W. It is further conceptualised that groundwater flows in and out of the GRU at open flow boundaries (non-perennial and Nzhelele Rivers), depending on the hydraulic head. The inflows into the GRU constitute the recharge. Additional recharge is from infiltration through the vadose zone. It is important to emphasise that fracture network analysis and exploration drilling are required for detailed understanding of the groundwater systems in the study area.

3.3 Aquifer characterisation

Pumping test data for 3 boreholes located within the study area were obtained from VSA Leboa Consulting Pty Ltd. Drawdown versus logarithm of time (s vs log t), drawdown versus time t in a log-log plot (log s vs. log t) and derivatives diagnostic plots were used to identify and characterise flow regimes from constant discharge data. These plots were matched to theoretical diagnostic plots to identify the aquifer type and characteristic flow regimes. Theoretical diagnostic plots include Theis model infinite two-dimensional confined, double porosity or unconfined, infinite linear no-flow boundary, infinite linear constant head boundary, leaky aquifer, well-bore storage and skin effect, infinite conductivity vertical fracture, general radial flow-noninteger flow dimension smaller than 2, general radial flow model-non-integer flow dimension larger than 2, combined effect of well bore storage and infinite linear constant head boundary. Detailed explanation of these diagnostic plots are found in Kruseman and de Ridder (2000), Renard *et al.* (2009) and Holland (2011).

Comparison of diagnostic plots (s vs log t, log s vs. log t and their derivatives) for H27-0052, H27-0138 and H27-0168 and theoretical diagnostic plots whose patterns matched those of these boreholes is shown in Figure 3.11. The diagnostic plots for these boreholes were constructed using AQTESOLV demo version. The theoretical diagnostic plots for variation 2 double porosity aquifer (Holland, 2011) are the ones that had patterns which are similar to those of boreholes in the study area. Thus, the aquifer in the study area can be categorised as a variation 2 double porosity type (Figure 3.11). The theoretical diagnostic plots for a variation 2 double porosity aquifer in Figure 3.11s are from Holland (2011). According to Holland (2011), the drawdown behaviour of this type of aquifer is characterised by distinct dips (fracture dewatering) during late times of the associated derivative data and stepwise drawdown.

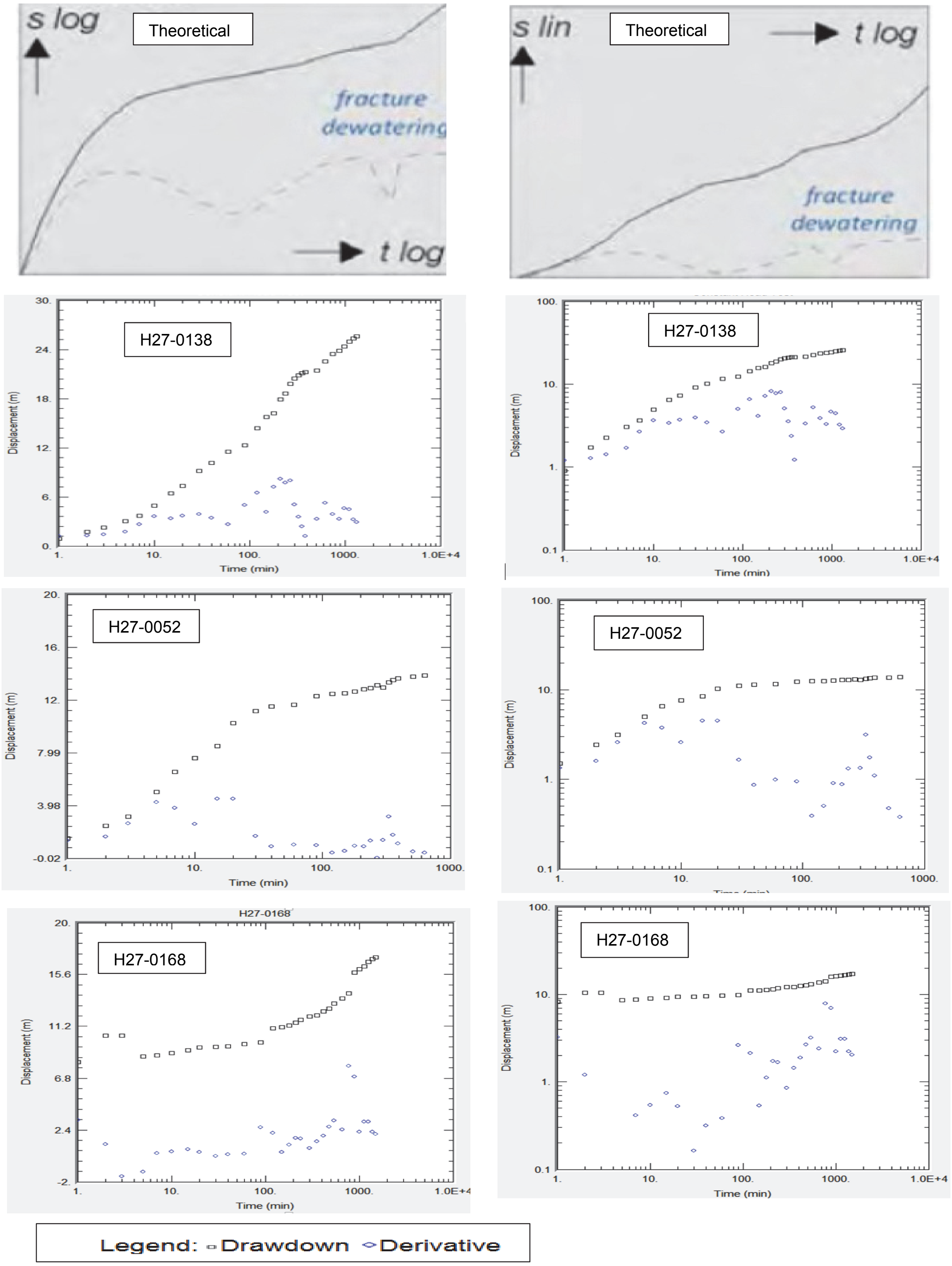


Figure 3.11: Diagnostic plots for theoretical and study area boreholes

Two drawdown measurements of 10.35 m for borehole H27-0168 shows anomalous behaviour as they deviated from the drawdown curve. Despite this, the aquifer is still classified as a variation 2 double porosity aquifer due to distinct dips (fracture dewatering) during late times of the derivative data. In a double porosity aquifer, matrix blocks have low permeability and high (primary) porosity and storage capacity, only the fractures produce flow directly to the well and matrix blocks act as a source, which feeds water into the fractures (Holland, 2011). Renard *et al.* (2009) explained that early pumping depletes the first reservoir (fractures, for example), which is then partly compensated by a delayed flux provided by a second compartment of the aquifer (second/intermediate stage) and equilibrium is reached at the late time (last stage). During the intermediate stage, drawdown stabilises and the derivative shows a pronounced hole (dip) (Renard *et al.*, 2009).

Kruseman and de Ridder (2000) categorised flow characteristics of double porosity aquifer into three time periods, which are:

- Early pumping time, when all the flow comes from storage in the fractures
- Medium pumping time, a transition period during which the matrix blocks feed their water at an increasing rate to the fractures, resulting in a (partly) stabilising drawdown;
- Late pumping time, when the pumped water comes from storage in both the fractures and the matrix blocks.

The flow regime characteristics described by Kruseman and de Ridder (2000) and Renard *et al.* (2009) apply to the study area since it is characterised by double porosity aquifer. This shows that the aquifer in the study area is also characterised by fracture dewatering. Fracture dewatering has an effect on groundwater levels depending on the abstraction rate (Van Tonder *et al.*, 2002). Sarathchhandra and Jayawardena (1995) also associated drying out of surface water resources to the dewatering cone extending along a linear rock fracture in Sri Lanka. Fracture dewatering should be avoided, whenever possible, because of the danger of mineral precipitation that can cause fracture and well clogging (Van Tonder *et al.*, 2002). The latter study noted that caution should be placed when assigning sustainable yields to boreholes in aquifers characterised by fracture dewatering. This therefore means that groundwater operating rules for aquifers characterised by fracture dewatering would aid in minimising impacts associated with fracture dewatering since they regulate water abstraction from the aquifer.

Pumping test data for 3 boreholes located within the study area obtained from VSA Leboa Consulting Pty Ltd were analysed using Flow Characteristics (FC) method (Van Tonder *et al.*, 2001) to compute the aquifer characteristics (storativity and transmissivity). The details of the boreholes and their locations are shown in Table 3.3. Table 3.4 shows the transmissivity values for boreholes H27-0052, H27-0138 and H27-0168 computed using Cooper Jacob method. They fall within the range of 1-24 m^2/day determined by Holland (2012) within the vicinity of the study areas. Storativity values could not be estimated based on the methods used in the FC programme. This was because the methods used in the FC programme are very insensitive to changes in drawdown and the calculated storativity values are therefore biased (Dippenaar, 2008). The pumping test reports from VSA Leboa Consulting (Pty) Ltd have reported storativity values of 0.0001 for all the boreholes listed in Table 3.4. Figure 3.12 shows locations of the boreholes within the study area.

Table 3.3: Borehole details

Borehole number	Latitude	Longitude	Altitude (m)	Date of test
H27-0052	30.190	22.301	805	1998/02/11
H27-0138	30.192	22.894	805	2003/02/14
H27-0168	30.188	22.904	780	1998/02/03

Table 3.4: Transmissivity and yield

BH number	T (m^2/day)	Recommended yield (l/s)		Constant pumping rate (yield) (l/s)
		10 hour duty cycle	24 hour duty cycle	
H27-0052	2.5	0.4	0.8	1.02
H27-0138	4.9	2.0	2.0	2.01
H27-0168	1.0	0.42	1.0	3.04

Storativity in confined aquifers fall within the range of $0.00005<S<0.005$ and they indicate that large pressure changes are required to produce substantial water yields (Todd and Mays, 2005). Storage coefficient (storativity) is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface (Borrocu, 2014). Thus, the aquifer in the study area is likely to store water in only 0.0001 (0.01 %) of its total storage volume.

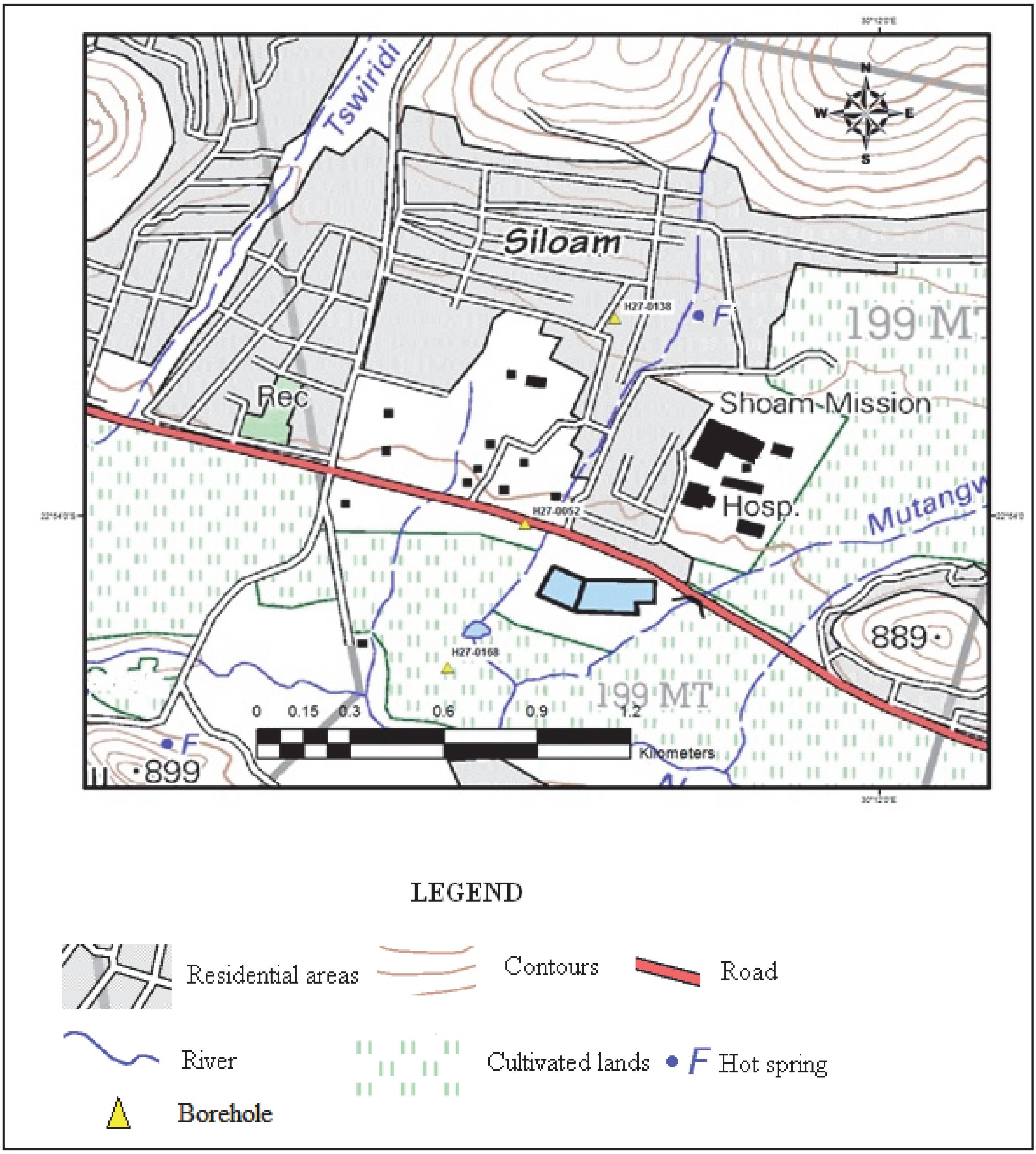


Figure 3.12: Boreholes locations

Transmissivities, recommended yields and constant pumping rates (Table 3.4) for the boreholes were mostly lower as compared to the average values of 514 boreholes which had average values of 35.1 m^2/day, 1.4 l/s, and 5.5 l/s, respectively, for similar aquifer type (variation 2 double porosity), which were obtained in a study by Holland (2011). Low transmissivity values indicate low rate of groundwater flow in the study area. It was only borehole H27-0138 which had higher recommended yield of 2.0 l/s. The rest of the boreholes had recommended yields which were lower than the average value of 1.4 l/s for the 514 boreholes. Factors such as geology, rainfall, topography and thickness of weathering are likely to cause variations in aquifer parameters.

4 DATA ACQUISITION

4.1 Preamble

This section presents data used for groundwater storage computation, groundwater storage-reliability analysis and derivation of operating rules. This includes rainfall, evapotranspiration, soil moisture, runoff, groundwater abstraction and groundwater quality data.

4.2 Rainfall, evapotranspiration and runoff

Patched rainfall data for station 0766324 for the period 1903/10/01-2000/07/31 (Figure 4.1) was obtained from Lynch (2003). This was the only data available since the station was closed in the year 2000. Rainfall and evapotranspiration for the period 2012-2013 (Figures 4.2 and 4.3, respectively) were obtained from the weather station installed at Siloam police station in Siloam Village for the purpose of this research project. Extended evapotranspiration data computed using the Hargreaves-Samani method for the period 1950-2000 (Figure 4.4) was obtained from Makungo (2009). The extension could only be done for this period since it was the only period when temperature data was available. Evaporation data for the period 2000-2012 was adopted from Mutshedzi weather station which had data from 1991/07/01 to 2012/01/12. Evaporation data from Mutshedzi weather station was used to compute evapotranspiration (Figure 4.5) for the period 2000-2012 based on the pan evaporation method (Equation 4.1) described in Allen *et al.* (1998).

$$ET_0 = E_P \times k \tag{4.1}$$

ET_0 is evapotranspiration, E_p is evaporation and k is the pan coefficient. The standard pan coefficient of 0.7 was used. University of Venda weather station at Siloam Village and Mutshedzi weather station are located in the same quaternary catchment (A80A) (Figure 4.6) and are expected to have similar hydrological behaviour. Runoff time series data for the GRU (Figure 4.7) was simulated using Australian Water Balance Model. This model has been selected because it achieved satisfactory to good model calibration and validation for the same study area in a study by Makungo (2009).

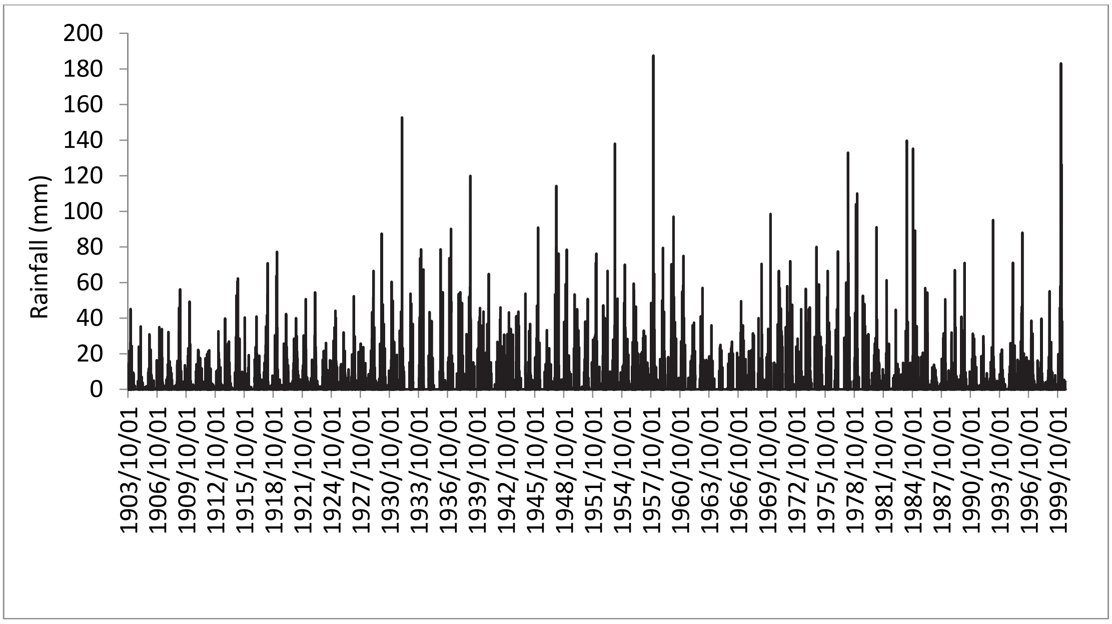


Figure 4.1: Rainfall data from 1903-1999

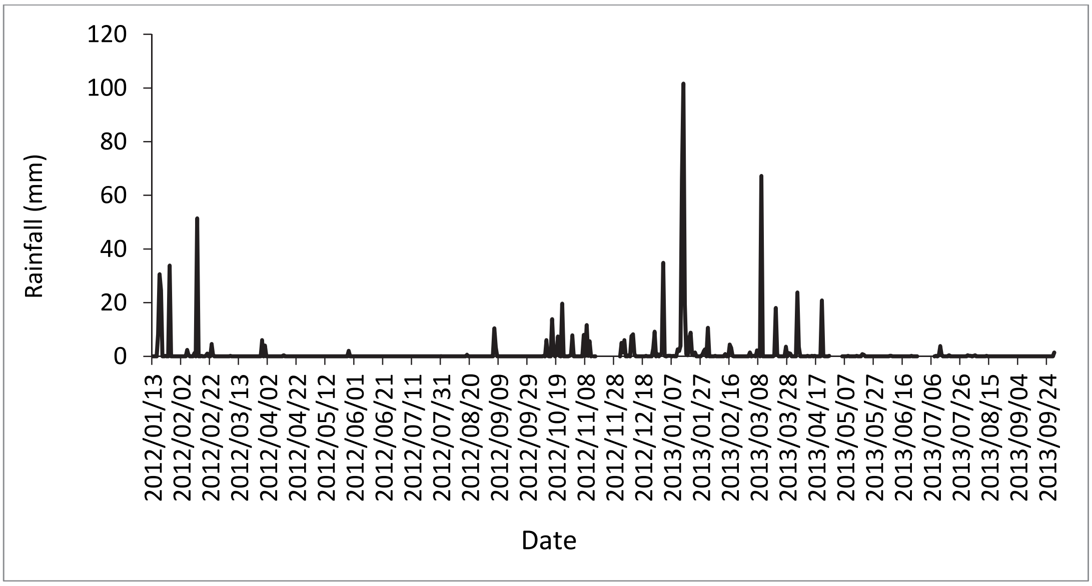


Figure 4.2: Rainfall data from 2012-2013

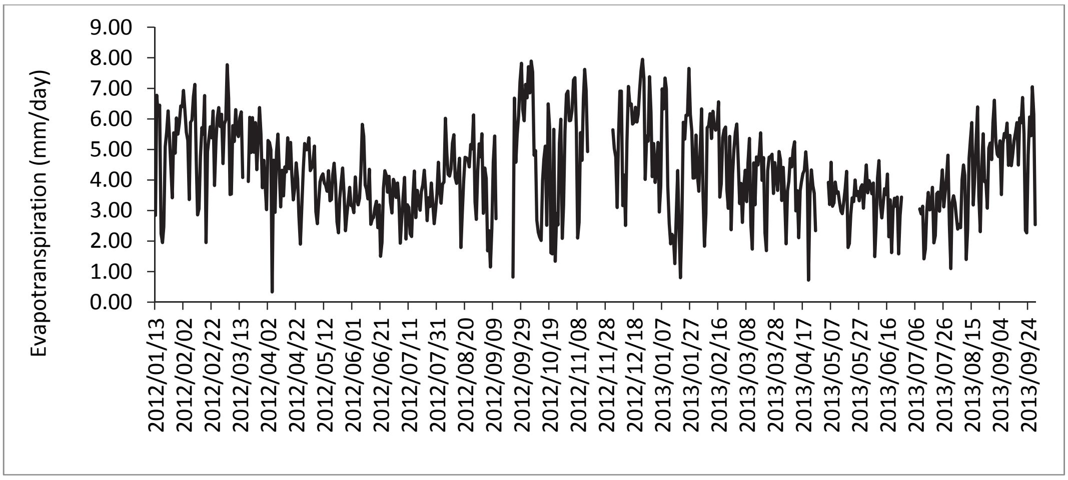


Figure 4.3: Evapotranspiration data from 2012-2013

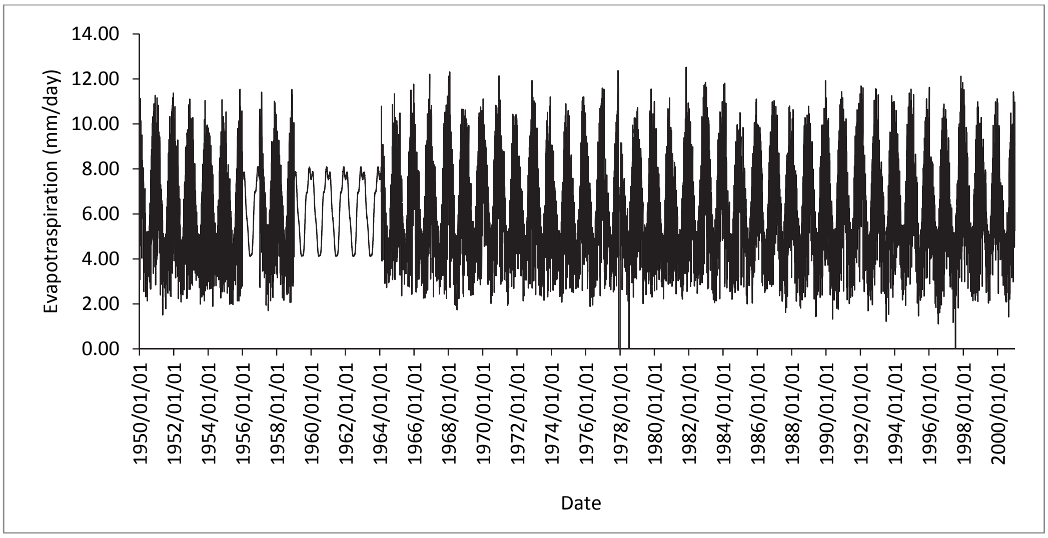


Figure 4.4: Evapotranspiration data from 1950-2000

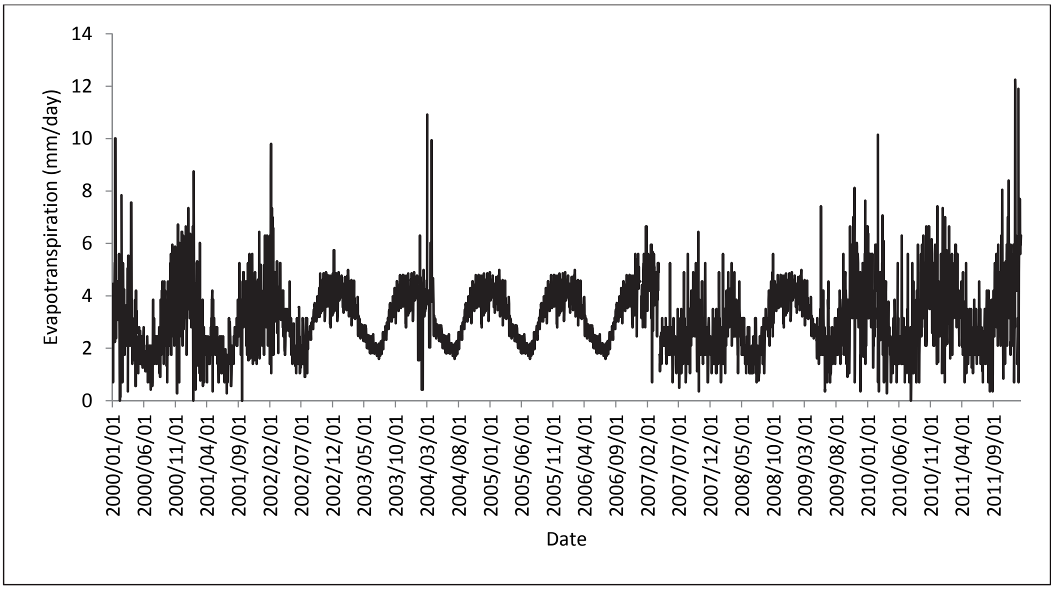


Figure 4.5: Extended evapotranspiration data

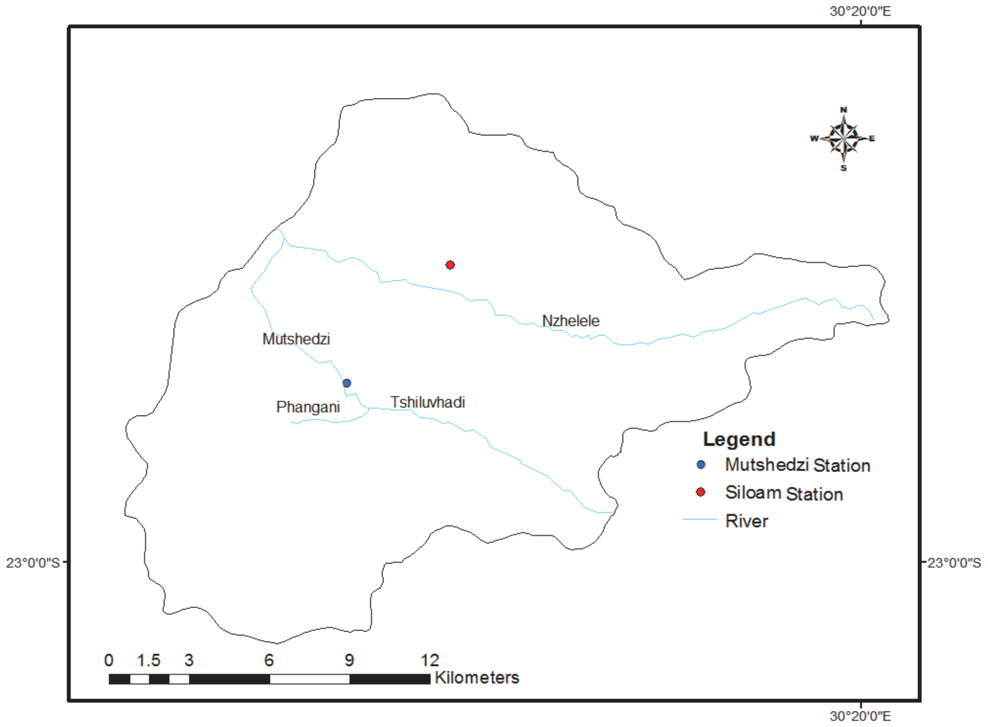


Figure 4.6: Location of Mutshedzi and University of Venda weather stations

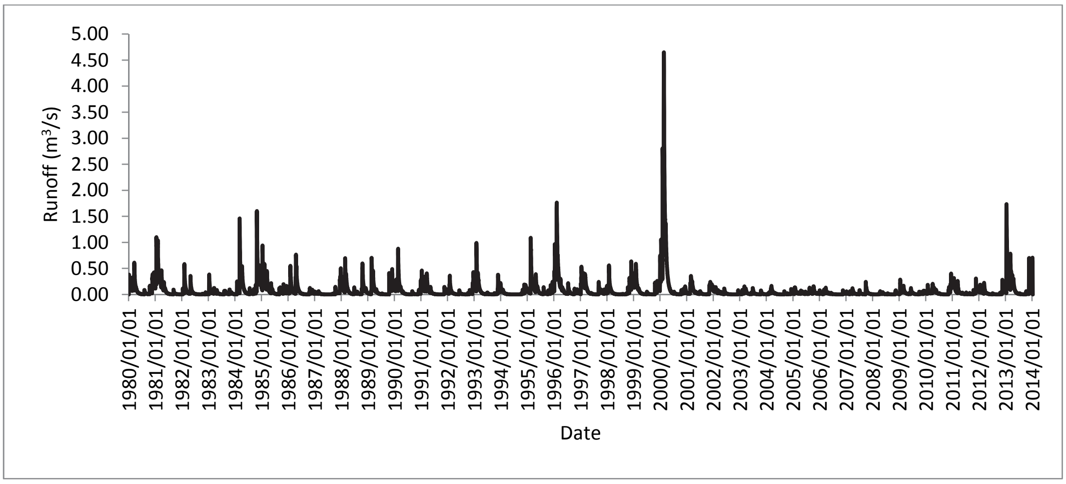


Figure 4.7: Runoff data from 1980-2014

4.3 Soil moisture

The distribution of the soil moisture monitoring probes is shown in Figure 4.8. Due to the rocky environment dominating the study area, it was not possible to install probes at some locations. Five short (80 cm) and long (180 cm) probes for measuring soil moisture were installed in Siloam Village in July 2011 and September 2012, respectively, to ensure automatic and continuous monitoring of soil moisture. The probes were installed at 8 sites and their identification numbers are given in Table 4.1. The 80 cm probes measured soil moisture at 10, 20, 30, 40, 60 and 80 cm depths while the 180 cm probes measured soil moisture at 30, 60, 90, 120, 150 and 180 cm depths. Daily soil moisture data for some of the probes for the periods July 2011-October 2013 and September 2012-October 2013 for short and long probes is shown in Figures 4.8 and 4.9, respectively. Only data which was used for soil moisture extension (at 80 and 180 cm depths) is presented in Figures 4.9 and 4.10.

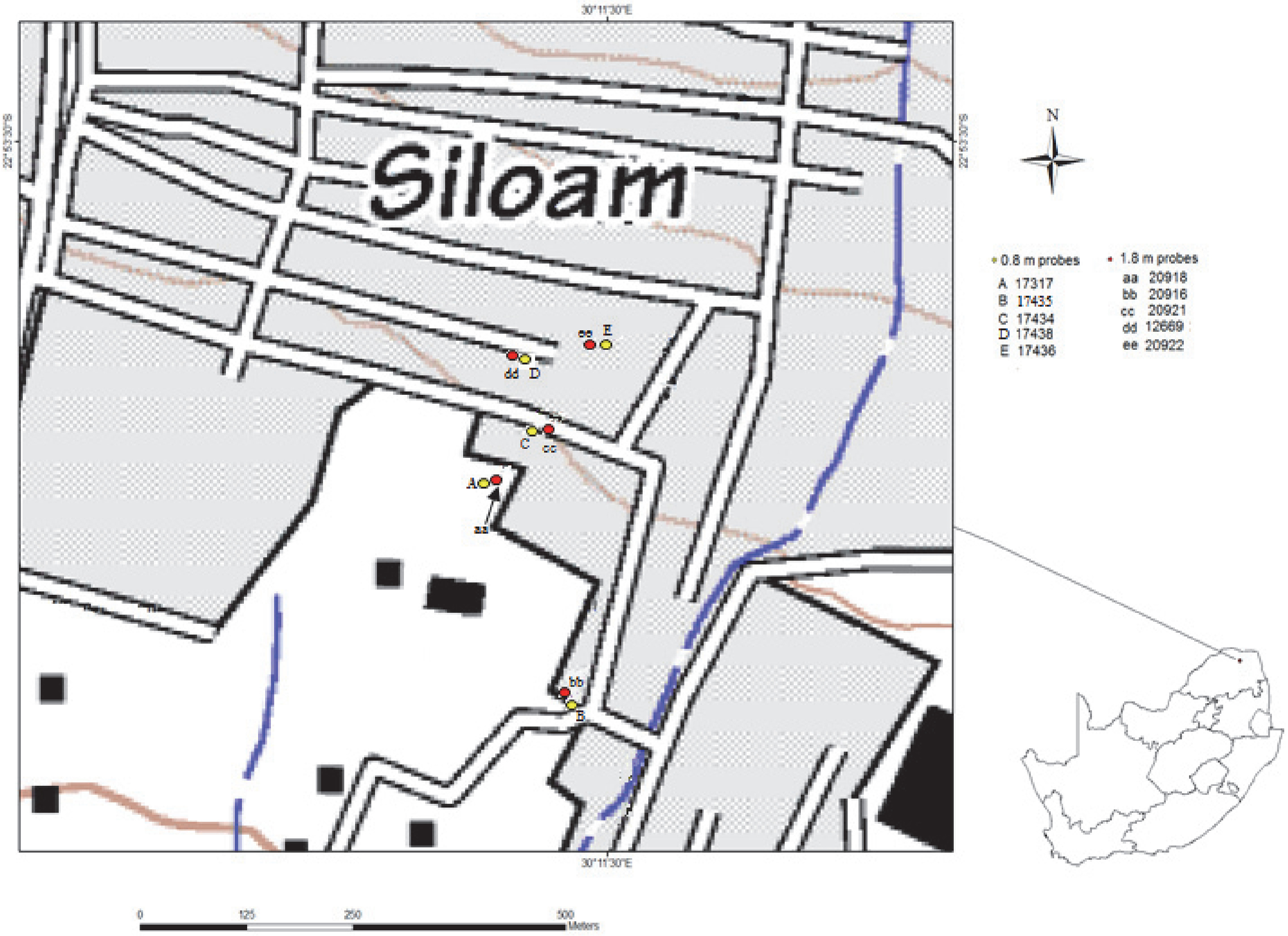


Figure 4.8: Distribution of soil moisture probes

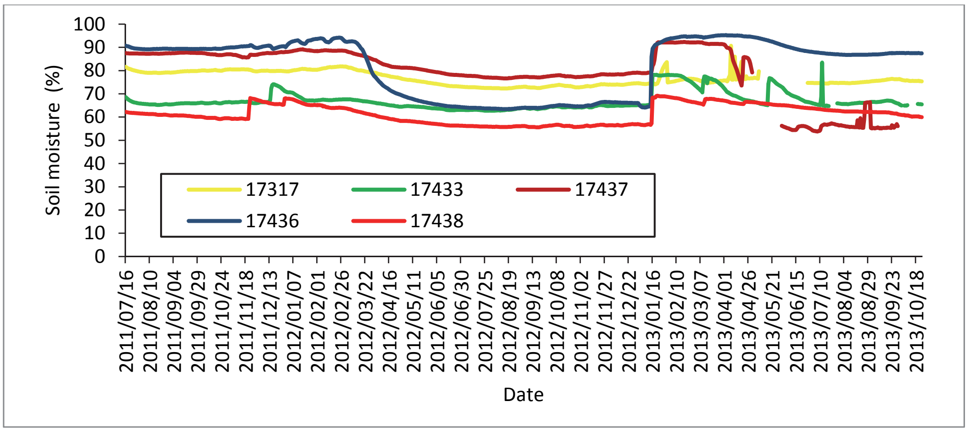


Figure 4.9: Soil moisture data for short probes

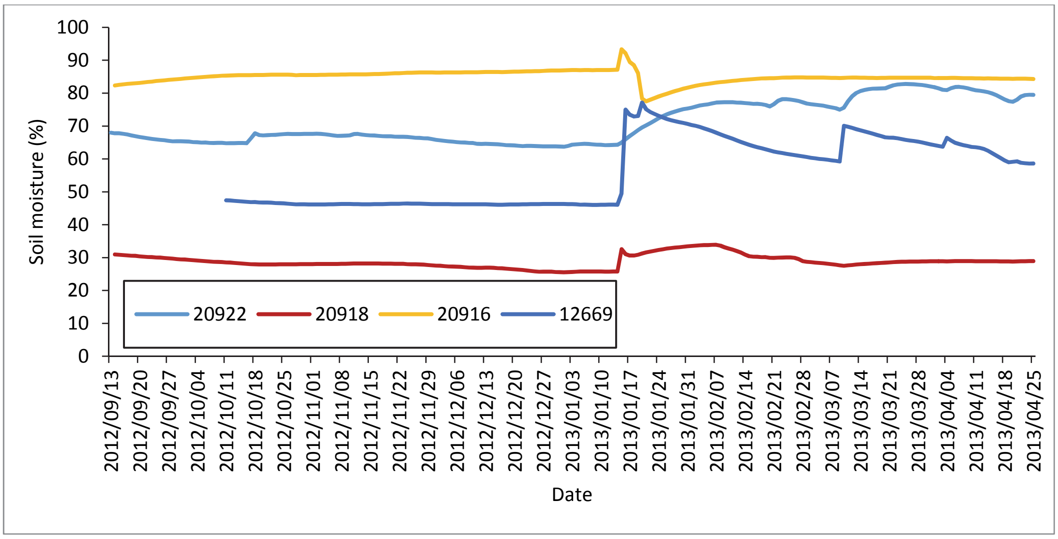


Figure 4.10: Soil moisture data for long probes

For the purpose of this study soil moisture at 80 and 180 cm for the short and long probes, respectively, are essential for recharge estimation. This is because root zone is at a depth of about 1 m. Arrey (2012) observed root zone depth at about 1 m in soil profiles dug at several sites in Siloam Village. Root zone of depths about 100-150 cm were recorded in savannah biomes of Limpopo Province in a study by Knoop and Walker (1985).

4.4 Groundwater abstractions

Groundwater abstractions for 10 private and 1 public boreholes are presented in Figure 4.11. The pump for the public borehole was not working from 24/12/2012 to 05/06/2013 and thus no abstractions took place during that period. The abstractions for this period shown in Figure 4.11 are for the private boreholes. Figure 4.12 shows the location of the boreholes in the study area.

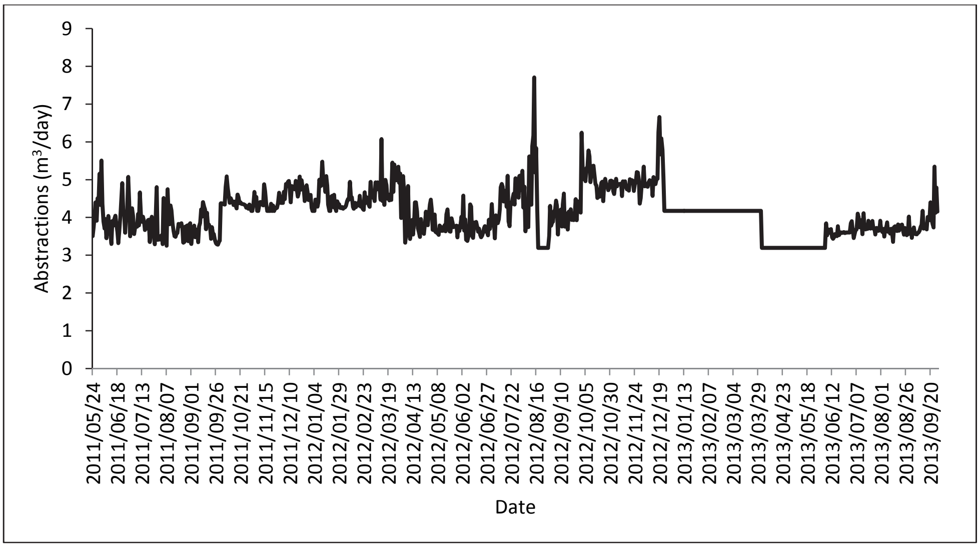


Figure 4.11: Borehole abstractions

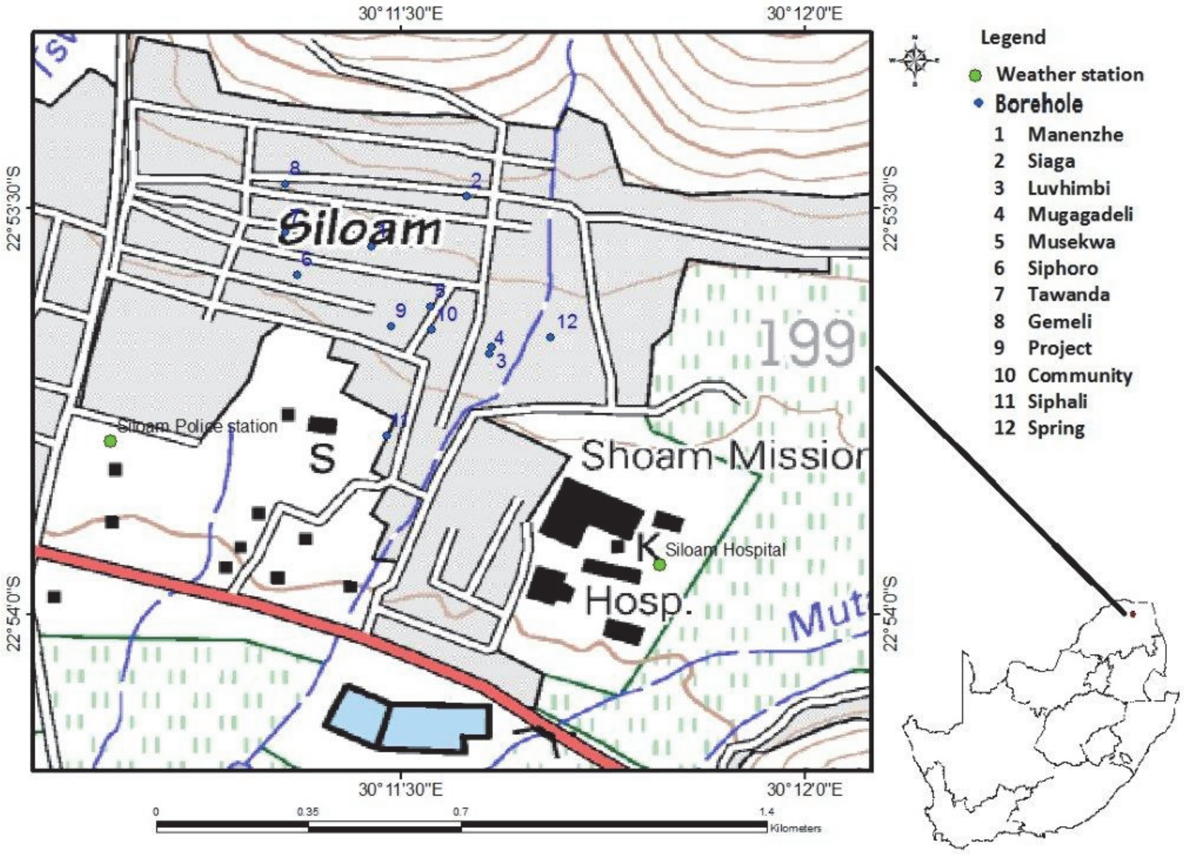


Figure 4.12: Location of boreholes

4.5 Groundwater quality

Turbidity, EC and pH were measured for the period May 2011 to April 2012 for private and public boreholes in the study area. Turbidity was measured using a calibrated Orion AQUAfast II turbidity meter while the pH and electrical conductivity were measured using a Multi 340i, Wissenschaftlich-Technische Werkstatten (WTW) multimeter. Additional data on chemical water quality (of the boreholes for the period May-October 2011) was obtained from Mafamadi (2012). Data on fluoride concentrations for the period August 2013 to January 2014 was obtained from Mukhumo (2014). These had been analysed using Ion Chromatography.

5 DATA EXTENSION: MODEL SET-UP, CALIBRATION AND VERIFICATION

5.1 Estimation of missing and extension of daily rainfall data using non-parametric regression (NPR)

Non-parametric regression (NPR) has been used to estimate missing rainfall data for the period 2000-2012. Regression analysis is often used in hydrology for exploring and presenting relationships between variables (Adamowski, 1987) and to provide predictions of unknown variables. NPR is one of the approaches used. It traces the dependence of a response variable on one or several predictors without specifying in advance the function that relates the predictors to the response (Fox, 2004). Non-parametric function estimation refers to methods that strive to approximate a target function locally, i.e., using data from a “small” neighbourhood of the point of estimate (Lall, 1995).

The general NPR model is written in a similar manner as linear regression, but the function f is left unspecified (Fox, 2002). Non-parametric method is suitable for analysis of multimodal distribution, which perhaps reflects more accurately the naturally occurring complex hydrological cycle (Adamowski, 1987). Adamowski (1987) reported that simulation results of studies by Adamoski (1985) and Labatiuk (1985) showed relative small values of bias and root mean square error as compared to Log-Pearson type III when used for flood frequency analysis. Lall (1995) gives the recent advances of application of NPR in hydrology. The reviewed applications included frequency analysis, classification, spatial surface fitting, trend analysis, time series forecasting and simulation of stochastic hydrology.

Non-parametric methods have also been applied in rainfall studies, though studies on estimation of rainfall are limited. A non-parametric approach based on k-nearest neighbour (KNN) estimator was used for spatial interpolation of rainfall data in a study by Ali (1998) and was able to deal with non-stationary environment, irregular data, and site geometry. The resulting statistics show a low estimation bias and a high variance. Kalra and Ahmad (2011) estimated seasonal precipitation by disaggregating water year precipitation for 29 climate divisions in the Colorado River Basin using a KNN non-parametric technique. The results indicated satisfactory estimation of seasonal precipitation during winter and spring seasons compared to autumn and summer seasons. The latter study also showed superiority of KNN approach when compared to a first-order periodic autoregressive parametric approach. Sharma and Lall (1999) used a non-parametric model to simulate daily rainfall spells and amounts in Sydney, Australia. The model was able to accurately represent non-stationarity of the rainfall generation mechanism and the seasonal characteristics of the observed rainfall. The study noted that the use of non-parametric methods enables accurate representation of the distributional features that characterise rainfall. The current review did not find any related studies that have been done in South Africa.

Other applications of non-parametric techniques in rainfall studies include development of nonparametric seasonal wet/dry spell stochastic model for resampling daily precipitation (Lall *et al.*, 1996), and stochastic generation of rainfall data (Rajagopalan and Lall, 1999; Harrold, 2002; Harrold *et al.*, 2003; Srikanthan *et al.*, 2005).

5.1.1 NPR modelling methodology

Daily rainfall data for Mutshedzi rainfall station was available for the period 1991/07/01 to 2012. This rainfall data was obtained from the Department of Water Affairs. It was essential to estimate rainfall data for Siloam weather station for the period 2000/08/01 to 2012/01/12 since it is one of the inputs into the groundwater balance. Rainfall for Mutshedzi and Siloam weather stations were used as inputs and outputs of the NPR model, respectively.

Daily rainfall data for the period 1991/07/01 to 2000/07/31 was used to calibrate and validate the non-parametric model since it was the period when data for the two stations was available. 60% (1991) and 40% (1328) data points were used for calibration and validation, respectively. These were the percentages that gave the best model performance after several trial runs. The data points used for calibration and validation were randomly selected by the model.

Daily rainfall data for Mutshedzi weather station for the period 2000/08/01 to 2012/01/12 was used to estimate rainfall data for Siloam weather station for the same period. Robust locally weighted scatter smoother (LOWESS) NPR method with kernel (tricube) weighting function (Equation 5.1) and two polynomial degrees was selected for this study. This method was selected because it gave the best results after running several trials using other non-parametric regression methods weighting functions.

$$W_T(z) = \begin{cases} \left(1-|z|^3\right)^3 & for\,|z|<1 \\ 0 & for\,|z|\geq 1 \end{cases} \tag{5.1}$$

$$z_i = \frac{(x_i - x_0)}{h_i}$$

z_i is the scaled distance between the predictor value for the i^{th} observation and x is the focal; h_i is the band width of the local regression centered on $x_{i.}$

Robust LOWESS was used to fit local polynomial regressions for all the estimation points and to join them together. This involved weighting each neighbouring data point according to a kernel weighting function, which assigns decreasing weight with distance from the point of estimation and then computes a weighted local polynomial regression model. Further details on robust LOWESS fitting procedure are found in Cleveland (1979) and Cleveland and Devlin (1988). The computations were automatically done in XLSTAT, which is an add-in component of Excel Spreadsheet. In general, the computations were according to the following steps:

- A fitting step where the best combination of model type, kernel weighting function, and bandwidth are obtained using the test sample;
- A validation phase that allows validation of the model on new observations;
- An application phase, where the model is applied to a new set of data to estimate the unknown variable.

The performance of the model was evaluated based on root mean square error (RMSE), mean square error (MSE), mean bias (BIAS), correlation coefficient (R) and coefficient of determination (R^2) (Equations 5.2-5.6).

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2 \right]^{\frac{1}{2}} \tag{5.2}$$

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2 \tag{5.3}$$

$$BIAS = \frac{1}{n} \sum_{i=1}^{n} (O_i - P_i) \tag{5.4}$$

$$R = \left[\frac{\sum_{i=1}^{n} (O_i - P_i)(O_i - \overline{P_i})}{\sqrt{\sum_{i=1}^{n} (P_i - \overline{P_i})^2 \sum_{i=1}^{n} (P_i - \overline{P_i})^2}} \right] \tag{5.5}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - P_i)(O_i - \overline{P_i})}{\sqrt{\sum_{i=1}^{n} (P_i - \overline{P_i})^2 \sum_{i=1}^{n} (P_i - \overline{P_i})^2}} \right]^2 \tag{5.6}$$

where O_i = observed rainfall (mm), P_i = estimated rainfall (mm), i= number of the day, n = total number of time steps and $\overline{P_i}$ is the mean rainfall.

RMSE and MSE are valuable because they indicate errors of the constituent of interest, which aids in analysis of the results (Moriasi *et al.*, 2007). RMSE gives an idea of the absolute differences between observed and modelled values in their original units of measurement (Hyndman and Koehler, 2006). R and R^2 describe the degree of co-linearity between simulated and measured data (Moriasi *et al.*, 2007; Obiero *et al.*, 2011). The coefficient of determination determines the proportion of in-situ variance that can be explained by the model (Rathjens and Oppelt, 2012). Bias measures the average tendency of the simulated constituent values to be larger or smaller than the measured data (Moriasi *et al.*, 2007).

5.1.2 NPR modelling results

The comparisons of observed and estimated rainfall for calibration and validation runs (Figures 5.1 and 5.2, respectively) show a general agreement between observed and simulated rainfall. A general visual agreement between observed and simulated constituent data indicates adequate calibration and validation over the range of the constituent being simulated (Singh *et al.*, 2004). LOWESS model was able to estimate low rainfall values for both calibration and validation runs relatively well. Peak rainfall events were mostly underestimated in both calibration and validation runs. For example, high peak rainfall events (> 40 mm) for the days 19 February 1995, 16 February 1996, and 06 February 2000 (Figure 5.1), and 18 February 1995, 11 January 1996 and 22 February 2000 (Figure 5.2) were underestimated in calibration and validation runs, respectively. Simolo (2010) reported that underestimation of intense precipitation events is a typical side effect of regression-based approaches. Ali (1998) also found that NPR approach failed to estimate the extreme rainfall values due to over smoothing.

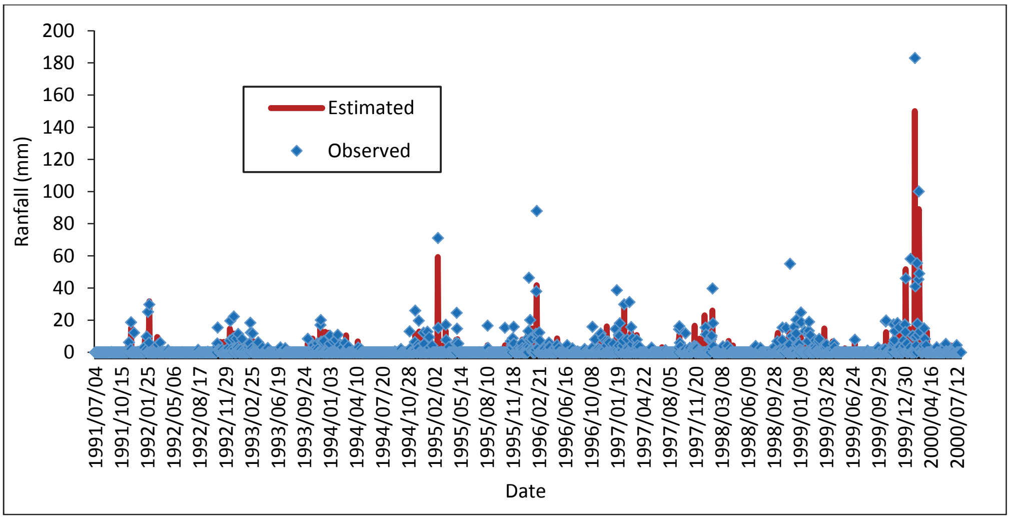


Figure 5.1: Observed and estimated rainfall for calibration run for stations

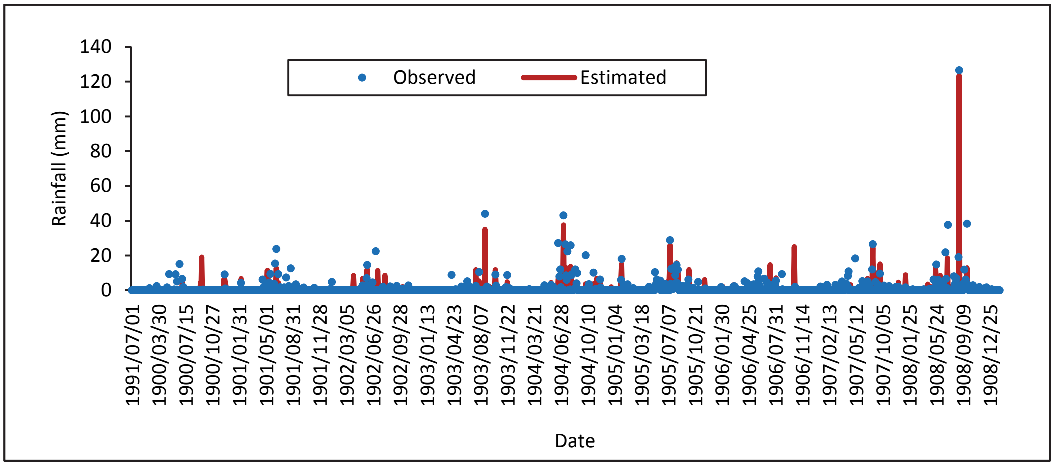


Figure 5.2: Observed and estimated rainfall for validation run for stations

Table 5.1 shows the performance measures for calibration and validation runs together with their acceptable ranges. RMSE and BIAS values for both the calibration and the validation

(Table 5.1) are reasonable as they are low and fall within the ranges obtained in other studies. RMSE of 64 mm was obtained in a study by Ali (1998). Kalra and Ahmad (2011) obtained RMSE values ranging from 0.44 to 2.69 inches, which are equivalent to a range of 11.18 to 68.33 mm. The relatively low computed BIAS values for calibration and validation show minimal estimation errors. These are lower than BIAS value of 7 mm, which was obtained in a study by Ali (1998). R values for calibration and validation exceed 0.8 showing satisfactory model performance. R^2 values exceed the acceptable value of 0.5 showing acceptable model performance. The model showed acceptable and satisfactory performance based on the assessed measures of performance. Thus, the model can effectively estimate missing rainfall for Siloam station. The estimated rainfall for Siloam Village is shown in Figure 5.3.

Table 5.1: Performance measures for calibration and validation runs

Performance Measure	Calibration	Validation	Acceptable ranges
RMSE (mm)	3.67	3.03	0 = Perfect[a]
BIAS (mm)	0.53	0.4	0 = Perfect[b]
R	0.87	0.84	>0.5 – Acceptable[c]; ≥0.80 – satisfactory[d]
MSE (mm)	13.48	9.19	0 = Perfect[c]
R^2	0.76	0.7	>0.5 – Acceptable[b]

[a]Shamsudin and Hashim (2002); [b]Elshamy (2008), [c]Van Liew *et al.* (2007); [d]Singh *et al.* (2004)

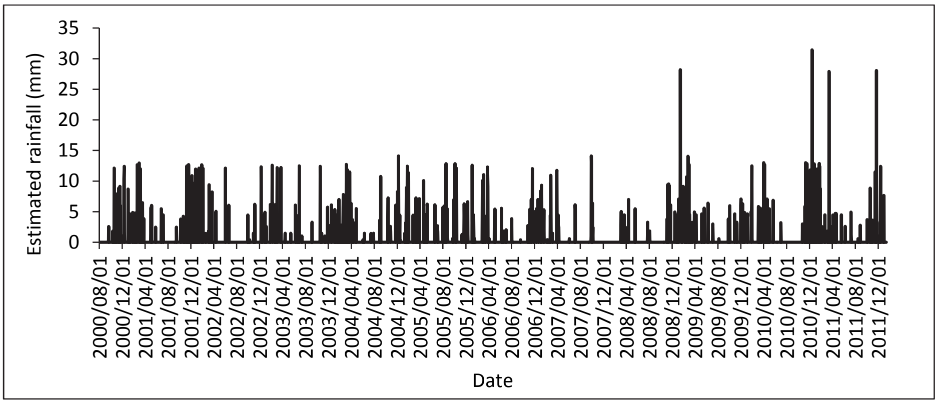


Figure 5.3: Estimated rainfall for Siloam Village

5.2 Extension of soil moisture data

A modelling code coupling a linear and a non-linear system identification models was used in the extension of soil moisture data. The code has the same structure as the one used in extension of groundwater levels. Within, the developed modelling code, a linear polynomial model is used to initialise the non-linear Hammerstein-Wiener model. The polynomial has model orders of number of past output terms used to predict current output (na), number of past input terms used to predict current output (nb) and delay from input to output in terms of number of samples (nk), and Output-Error (OE) model structure. The initialisation configures the non-linear Hammerstein-Wiener model to use orders and delays of the linear model, and polynomials as the transfer functions (Ljung, 2014). This initialisation aids in improving the fit of the model. OE model structure is one of the various linear model structures that provide different ways of parameterising the transfer functions of linear input-output polynomial model within system identification software (Ljung, 2014).

Hammerstein-Wiener models describe dynamic systems using one or two static nonlinear blocks in series with a linear block. Detailed description of these models is provided in Ljung (2014). Selected model orders for each probe are shown in Table 5.2. These model orders were selected because they gave the best results after several trial runs. Although monitored soil moisture data was available for 5 probes, only 3 could be used for modelling and extension. This was because two of the probes had a lot of gaps that could not be patched.

Table 5.2: System model orders

Probe	Model orders (na, nb, nk) used
20918	1,1; 4,4; 1,1
20922	4,4; 4,4; 3,3
12699	2,2;1,1;1,1

Figures 5.4-5.6 show observed and estimated soil moisture for calibration and validation runs. The comparisons of observed and estimated soil moisture for calibration and validation runs show agreement between observed and simulated soil moisture. Measures of performance (Table 5.3), which are within acceptable ranges support this. Extended soil moisture data is presented in Figure 5.4.

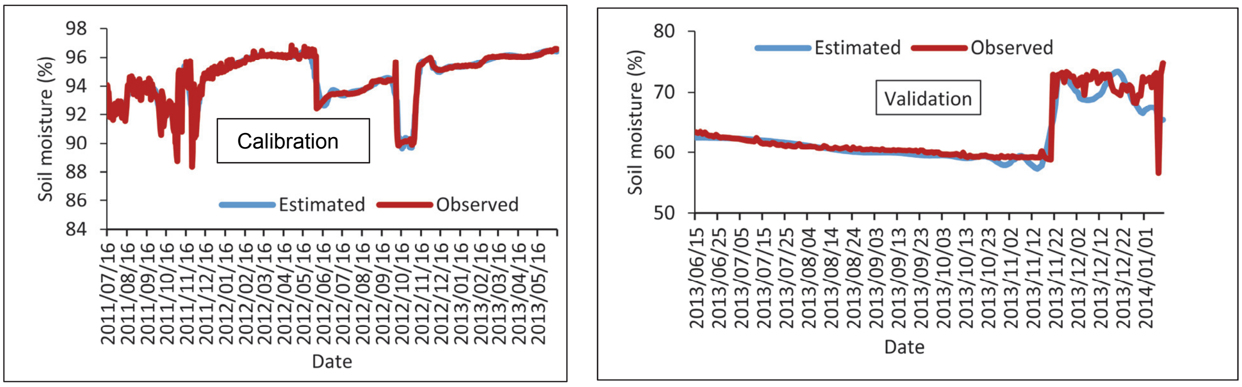


Figure 5.4: Observed and estimated soil moisture for calibration and validation runs for probe 12699

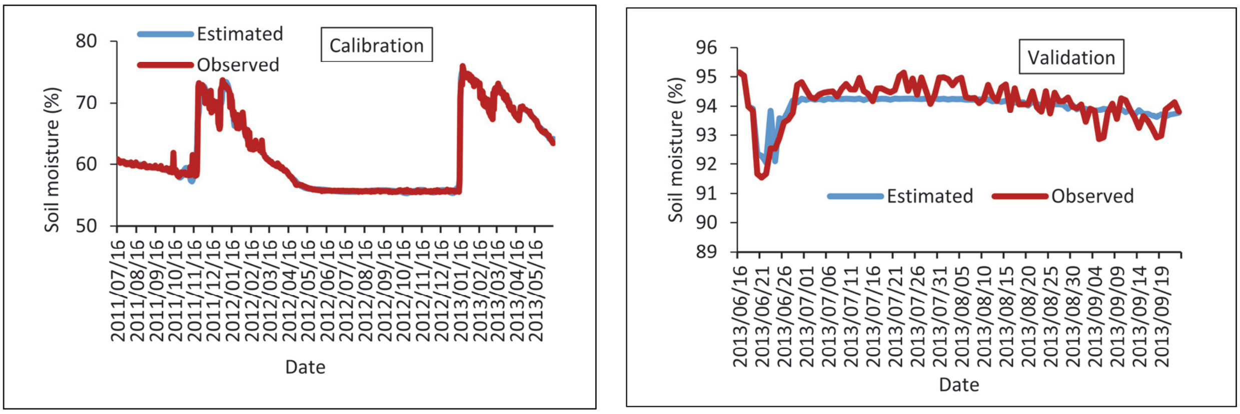


Figure 5.5: Observed and estimated soil moisture for calibration and validation runs for probe 20918

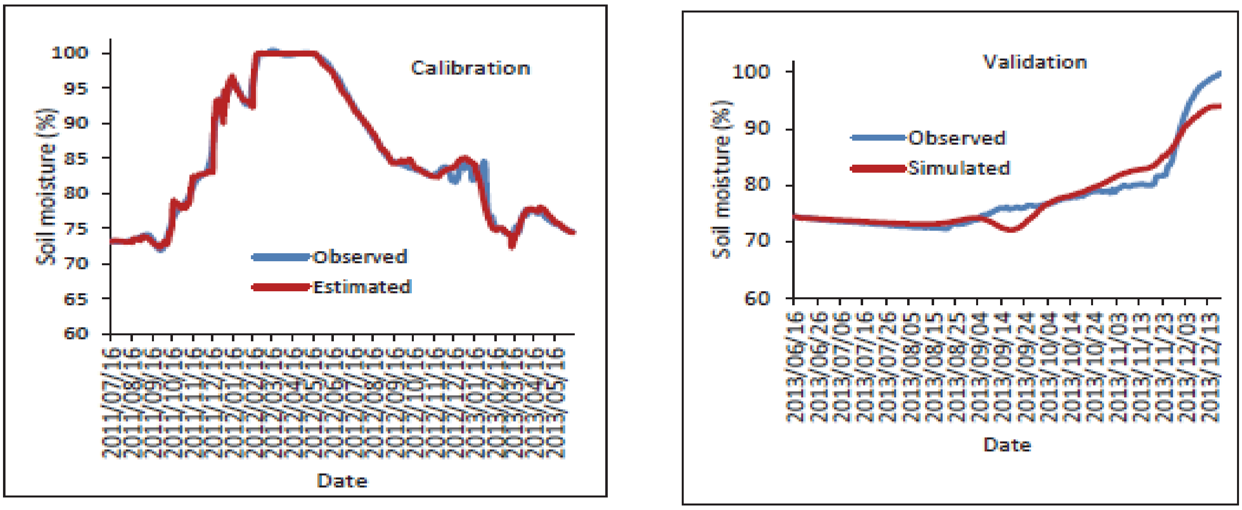


Figure 5.6: Observed and estimated soil moisture for calibration and validation runs for probe 20922

Table 5.3: Computed measures of performance and their acceptable ranges

Performance Measure	12699		20922		20918		Acceptable values
	Cal	Val	Cal	Val	Cal	Val	
Coefficient of determination (R^2)	0.993	0.93	0.90	0.95	0.96	0.71	>0.5 – Acceptable[b]
Correlation coefficient (R)	0.996	0.87	0.95	0.97	0.98	0.81	>0.5 – Acceptable[c]; ≥ 0.80 – satisfactory[d]
RMSE (%)	0.31	1.38	1.23	2.38	0.18	0.18	0 = Perfect[a]
MSE (%)	0.51	1.90	1.50	5.70	0.42	0.43	0 = Perfect[a]

[a]Shamsudin and Hassim (2002); [b]Elshamy (2008), [c]Van Liew *et al.* (2007); [d]Singh *et al.* 2004

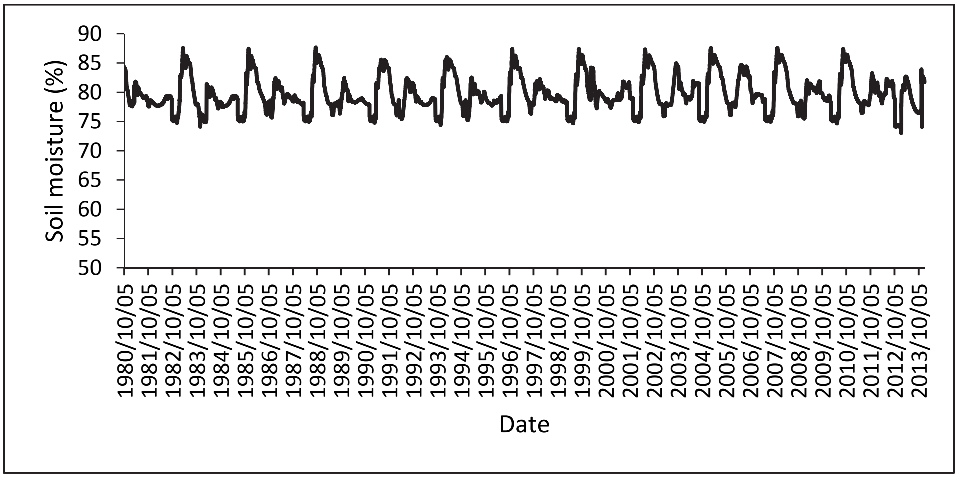


Figure 5.7: Extended soil moisture

6 GROUNDWATER STORAGE-RELIABILITY ANALYSIS AND OPERATING RULES

6.1 Groundwater storage-reliability analysis

Though the study had proposed groundwater yield-reliability analysis for the purpose of developing groundwater operating rules, this was not possible due to lack of long-term time series of groundwater yield data in the study area. Groundwater storage-reliability analysis was used as an alternative approach that made it possible to develop groundwater operating rules. Groundwater storage-reliability analysis involved the computation of weekly groundwater storages and their reliability. Computation of groundwater storage time series was done following the hydrological year (October of a given year to September of the following year). The weekly change in groundwater storage time series was computed using the groundwater balance (Equation 6.1).

$$P - R_o - ET \pm \Delta s \pm Q_{io} - Q_a = \pm \Delta G \tag{6.1}$$

where P= precipitation, R_o= runoff, ET= evapotranspiration, Δs= change in soil water storage, Q_{io}= inflow/outflow at open flow boundaries, Q_a = groundwater abstraction and ΔG = change in groundwater storage. The runoff component of the equation is comprised of both storm runoff and baseflow and thus, accounts for groundwater loss into the river during the dry season. Groundwater storage was computed at a weekly scale since it was envisaged that there would be no significant difference in groundwater storage at a daily scale. Weekly groundwater storage time series was computed from Equation 6.2.

$$G_{t+1} = G_t \pm \Delta G \tag{6.2}$$

G_t and G_{t+1} are the storages at periods t and $t+1$, respectively. G_t was estimated by computing the total storage volume of the groundwater reservoir (G_{Total}) using Equation 6.3. This was used to compute groundwater storage time series, assuming that the groundwater reservoir was at full storage level (100% saturation) at the beginning of the analysis (i.e. at time, t). To account for possible variations in groundwater storage at time, t, groundwater storage time series was also computed for scenarios assuming 80, 60, 40, 30, 25, 20 and 10% of full groundwater reservoir storage level (GRSL). Groundwater storage reservoir has been used in this study to refer to the portion of the GRU where groundwater is stored in interconnected fractures, faults, cracks and/or openings in the aquifer.

$$G_{Total} = A \times h \times S \tag{6.3}$$

Where *A*= area of the GRU, *h*=saturated thickness of the aquifer and *S*= storativity. There were no values of saturated aquifer thickness from the pumping test data for the 3 boreholes in the study area. However, most of South Africa's accessible groundwater is stored in the upper fractured and weathered zone whose saturated thickness was found to be 25 m (Vegter, 1995). This value is closer to the maximum drawdown of 25.6 m from pumping test data for borehole H27-0138 (Figure 3.11). The maximum drawdowns from pumping test data for boreholes H27-0052, H27-0168 and H27-0138 (Figure 3.11), which are 17.23, 19.1 and 25.6 m, respectively, would indicate variable average saturated aquifers thicknesses. Since drawdown levels data could only be obtained from 3 boreholes, it was considered appropriate to adopt the average saturated thickness of 25 m from Vegter (1995), which would be more representative of the average spatial saturated thickness of the aquifer in the study area.

Values for each week of the year from October 1980 to September 2013 were extracted from the computed groundwater storage time series such that 52 data sets, each with 33 data points for each storage scenario, were generated. These were ranked in ascending order and their reliability was calculated using Weibull plotting position formula (Equation 6.4).

$$p = \frac{m}{n+1} \tag{6.4}$$

p is the probability that the magnitude ranked *m* is exceeded for a ranked series that is *n* years long. The reliability associated with the magnitude ranked *m* was obtained as reliability = 100*p*% following Ndiritu *et al.* (2011a). Figure 6.1 shows the computed groundwater storage for the period 1980-2013 for 100% of GRSL. This represents the volume of water stored within the GRU. The flood which occurred in the 1996/97 hydrological year contributed to a rise in groundwater storage, which was continuously maintained by the 1999/2000 and subsequent hydrological year floods. The other floods include 2010/2011 and 2012/2013, though they were of lower magnitude as compared to the 1999/2000 flood. This explains generally higher groundwater storage after the year 1996 as compared to the years before.

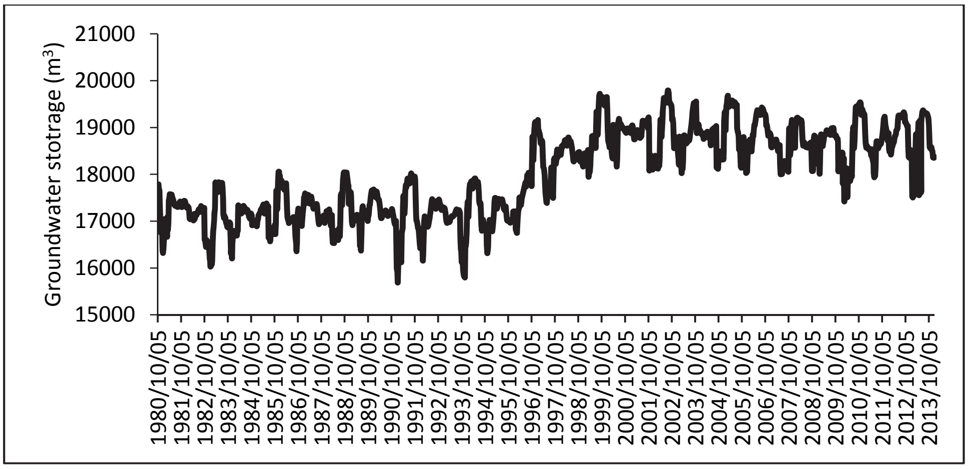


Figure 6.1: Computed groundwater storage time series at full storage level

Examples of groundwater storage-reliability curves for selected weeks of the year at 10, 20, 40, 60, 80 and 100% of GRSLs are shown in Figure 6.2. These have been extracted from Appendix A. The curves show groundwater storages available at different reliabilities within specific weeks and they form the basis of deriving groundwater operating rules, since they give an indication of storages, which would ensure adequate supply of groundwater. The dates that fall within each specific week are in Table 6.1. Weeks 1, 10, 20, 30, 40 and 50 covers the weeks starting on the dates of 1980/10/06, 1980/12/07, 1981/02/15, 1981/04/26, 1981/07/05 and 1980/09/13 (Table 6.1). These have been used to represent the weeks, which fall in the wet and dry rainfall seasons. This is useful when assessing the availability of groundwater throughout the year.

Relatively high and low storages are associated with low and high levels of reliability, respectively. For example, storages with 10% reliability are higher than those with 98% reliability. This is because high storages are a result of heavy rainfall events which rarely occur as compared to normal rainfall events. Thus, the reliability of such high rainfall events is generally low. However, in terms of groundwater storage, such rainfall events are significant since they significantly increase the groundwater storage, which may be available for use during dry periods. Thus, heavy rainfall events contribute to major recharge events. Van Wyk *et al.* (2012) reported that episodic rainfall events are responsible for rapid, but sustainable groundwater recharge events in semi-arid areas of South Africa.

Since, the risk (R) of failure of a water supply source is calculated as $R = 1 - p$, where p is the reliability, storages with low and high levels of reliability, are thus associated with high and low risk of failures, respectively. This therefore means that groundwater storages with high levels of reliability are the ones that can ensure continuous and adequate supply with low risk of failure. The volume of water in storage increases as the percentage storage volume increases, hence 100% storage has highest storage volumes (Figure 6.2).

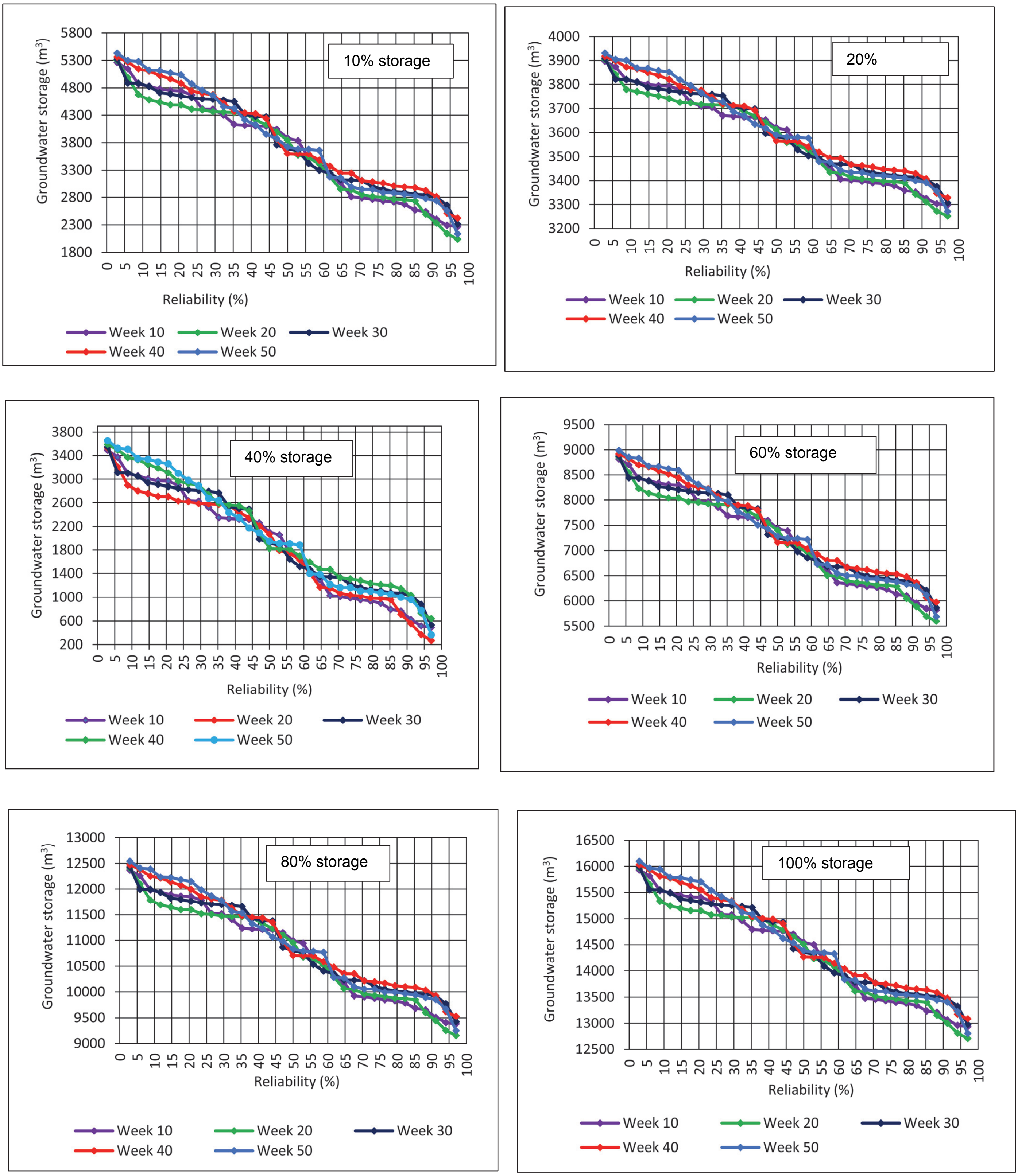


Figure 6.2: Weekly groundwater storage-reliability curves

Table 6.1: Weekly start and end dates

Week	Start date	End date	Week	Start date	End date
1	1980/10/06	2012/10/07	27	1981/04/05	2013/04/07
2	1980/10/12	2012/10/14	28	1981/04/12	2013/04/14
3	1980/10/19	2012/10/21	29	1981/04/19	2013/04/21
4	1980/10/26	2012/10/28	30	1981/04/26	2013/04/28
5	1980/11/02	2012/11/04	31	1981/05/03	2013/05/05
6	1980/11/09	2012/11/11	32	1981/05/10	2013/05/12
7	1980/11/16	2012/11/18	33	1981/05/17	2013/05/19
8	1980/11/23	2012/11/25	34	1981/05/24	2013/05/26
9	1980/11/30	2012/12/02	35	1981/05/31	2013/06/02
10	1980/12/07	2012/12/09	36	1981/06/07	2013/06/09
11	1980/12/14	2012/12/16	37	1981/06/14	2013/06/16
12	1980/12/21	2012/12/23	38	1981/06/21	2013/06/23
13	1980/12/28	2012/12/30	39	1981/06/28	2013/06/30
14	1981/01/04	2013/01/06	40	1981/07/05	2013/07/07
15	1981/01/11	2013/01/13	41	1981/07/12	2013/07/14
16	1981/01/18	2013/01/20	42	1981/07/19	2013/07/21
17	1981/01/25	2013/01/27	43	1981/07/26	2013/07/28
18	1981/02/01	2013/02/03	44	1981/08/02	2013/08/04
19	1981/02/08	2013/02/10	45	1981/08/09	2013/08/11
20	1981/02/15	2013/02/17	46	1981/08/16	2013/08/18
21	1981/02/22	2013/02/24	47	1981/08/23	2013/08/25
22	1981/03/01	2013/03/03	48	1981/08/30	2013/09/01
23	1981/03/08	2013/03/10	49	1981/09/06	2013/09/08
24	1981/03/15	2013/03/17	50	1981/09/13	2013/09/15
25	1981/03/22	2013/03/24	51	1981/09/20	2013/09/22
26	1981/03/29	2013/03/31	52	1981/09/27	2013/09/29

6.2 Groundwater quality assessment

The measured pH, turbidity and EC values from May 2011 to April 2012 are shown in Table 6.2. Two of the sampled boreholes (Communal and Hot spring) had pH values which were a slightly higher than DWAF (1996) water quality guideline for domestic use of 6-9 in the months of October 2011, and September and December 2011, respectively. These pH values do not have any potential health effects but only have a slight soapy taste in drinking water and insignificant effects on bathing. Turbidity values for most of the boreholes were generally higher than 1 NTU provided in the DWAF (1996) guideline. Thus, there is a slight risk of potential health effects caused by turbidity as stated in DWAF *et al*. (1998) in most boreholes. Incomplete borehole development such as lack of installations of screens in boreholes drilled in hard rock aquifers contributes to disintegrated rock particles or eroded sediments increasing turbidity levels. Three of the sampled boreholes (Community, Hot spring and Project) had EC values within the guideline of less than 70 mS/m. Siphali, Siaga, Gemeli, Manenzhe, Musekwa and Luvhimbi boreholes had EC values ranging from 208 to 2070 mS/m. Effects of these high EC values include distinct and extreme salty and bitter taste in water, slight possibility of salt overloading in sensitive groups, corrosion in laundry, impaired soap lathering and increasing risk of dehydration. However, for Siphoro, Mugagadeli and Tawanda boreholes, EC varies from 4 to 125 mS/m, that is, from acceptable to unacceptable values.

Analysed non-metals in groundwater from sampled boreholes are shown in Figure 6.3. Most boreholes had fluoride (F) concentrations, which were far much higher than the DWAF (1996) guideline of 1.5 mg/L (Figure 6.3). Effects associated with these concentrations are severe tooth staining from drinking water and increased risk of health effects from food preparation. A survey by Odiyo *et al.* (2012) revealed that 85% of family members from 87% of households that use groundwater have mottled teeth due to high fluoride concentrations in groundwater. 50% of children between the ages of 11 and 14 in Siloam Primary School also had mottled teeth (Odiyo *et al.*, 2012). Most boreholes had chloride concentrations exceeding the DWAF (1996) guideline of <100 mg/L. Effects of such concentrations include possible long-term health effects for cooking and drinking, objectionable salty taste and corrosion in laundry. Siphali is the only borehole that had high sulphate (SO_4) concentrations exceeding DWAF (1996) water quality guideline in the months of May and October 2012. The concentrations are associated with possible slight corrosion of laundry but suitable for all the other domestic uses. All boreholes had nitrate concentrations, which were less than DWAF (1996) guideline of <26 mg/L. Water from a few boreholes exceeded the SABS 241 (1996) guideline for phosphate (PO_4) in drinking water of 15 mg/L.

Table 6.2: Turbidity, EC and pH values

TURBIDITY												
DATE	COM	HSP	SI	SO	MG	PT	TA	SA	MAN	MUS	LI	GE
May-11	0.7	4.4	0.5	2.9	0.2	0.2	1.2	0.3	2.2	11.5	4.2	7.4
Jun-11	5.6	4.3	0.3	3.4	0.6	0.1	0.1	2.1	0.9	6.3	6.0	7.0
Jul-11	4.1	1.2	2.9	2.0	9.7	1.3	1.6	0.1	1.9	2.3	8.3	9.4
Aug-11	2.0	4.4	3.5	2.7	4.5	0.2	3.4	0.5	1.0	0.1	10.1	10.3
Sep-11	2.3	1.8	2.3	2.3	3.0	2.0	1.9	1.1	2.3	1.0	12.5	4.3
Oct-11	0.7	1.5	3.4	2.6	3.8	0.4	1.6	0.2	2.2	1.9	9.1	9.9
Nov-11	5.0	4.3	1.9	1.5	1.7	7.7	6.9	3.6	5.4	1.1	3.8	3.6
Dec-11	5.7	0.2	6.5	5.8	2.8	4.5	Nm	4.6	4.7	4.2	5.9	4.6
Jan-12	4.6	4.9	6.2	5.1	1.9	1.4	4.0	5.2	5.1	3.4	7.8	5.2
Feb-12	13.3	7.9	10	8.1	10.6	15.5	11.3	13	10.3	16.5	11	13
Mar-12	2.2	2.0	2.5	1.9	0.01	Nm	6.8	2.8	3.0	2.3	2.9	0.3
Apr-12	nm	2.2	2.1	2.1	2.2	2.0	nm	2.3	2.1	3.2	0.8	2.0
pH												
DATE	COM	HSP	SI	SO	MG	PT	TA	SA	MAN	MUS	LI	GE
May-11	7.6	8.8	7.6	7.6	8.1	7.9	7.2	7.7	7.6	8.3	8.0	7.7
Jun-11	8.6	8.3	8.0	7.7	8.1	7.7	7.4	7.9	7.7	8.6	8.0	7.6
Jul-11	8.6	8.9	7.7	8.0	8.2	7.8	7.1	7.9	7.8	8.6	7.9	7.3
Aug-11	8.9	9.0	7.4	8.0	8.4	8.5	7.4	7.9	7.5	8.7	7.9	7.9
Sep-11	9.0	9.1	7.0	7.5	9.0	8.4	7.1	7.5	7.6	8.8	8.1	7.4
Oct-11	9.1	9.0	7.1	7.3	8.7	8.6	7.1	7.5	7.6	8.7	8.3	7.1
Nov-11	8.3	9.0	7.5	7.6	7.6	8.2	7.7	7.6	7.5	8.2	8.4	7.2
Dec-11	9.0	9.1	7.4	8.3	8.5	8.1	nm	7.91	7.5	8.7	8.0	7.4
Jan-12	8.7	8.9	7.3	8.3	8.5	8.0	7.11	7.47	7.5	8.7	8.3	7.1
Feb-12	8.9	8.8	6.9	7.0	7.8	8.0	7.54	6.99	7.1	8.5	7.5	6.9
Mar-12	6.7	6.8	6.8	6.8	6.8	Nm	6.74	6.83	6.8	6.8	6.7	nm
Apr-12	6.7	6.7	6.7	6.7	6.7	6.6	6.67	6.7	6.7	6.7	6.7	6.7
EC												
DATE	COM	HSP	SI	SO	MG	PT	TA	SA	MAN	MUS	LI	GE
May-11	37.7	32.8	224.0	104.7	48.9	37.1	4.0	1769.0	1926.0	763.0	1324.0	1899.0
Jun-11	34.3	32.8	221.0	115.7	69.8	37.6	4.1	1662.0	1887.0	740.0	1028.0	2070.0
Jul-11	33.8	33.5	222.0	122.9	83.0	37.5	54.3	1641.0	1953.0	739.0	1163.0	2020.0
Aug-11	33.5	33.3	218.0	124.6	62.3	40.5	56.1	1722.0	1981.0	741.0	1017.0	1934.0
Sep-11	34.9	33.3	240.0	125.1	37.3	41.7	60.4	1721.0	1940.0	136.0	1166.0	2050.0
Oct-11	33.9	33.3	258.0	125.0	48.6	39.7	80.6	1653.0	1884.0	750.0	1172.0	2050.0
Nov-11	33.0	32.7	247.0	12.2	64.8	41.6	76.2	1110.0	1228.0	362.0	695.0	1237.0
Dec-11	33.3	32.7	208.0	12.0	44.8	41.1	nm	1097.0	1305.0	415.0	724.0	1386.0
Jan-12	32.8	33.4	230.0	12.3	37.4	37.8	84.4	1117.0	1280.0	355.0	526.0	1172.0
Feb-12	32.9	32.4	243.0	12.5	46.6	38.4	83.9	1123.0	1321.0	356.0	631.0	1185.0
Mar-12	33.8	33.2	233.0	12.5	90.5	Nm	39.0	1559.0	1326.0	367.0	630.0	1160.0
Apr-12	32.8	32.3	220.0	12.1	52.7	37.9	28.2	993.0	1340.0	156.0	556.0	1199.0

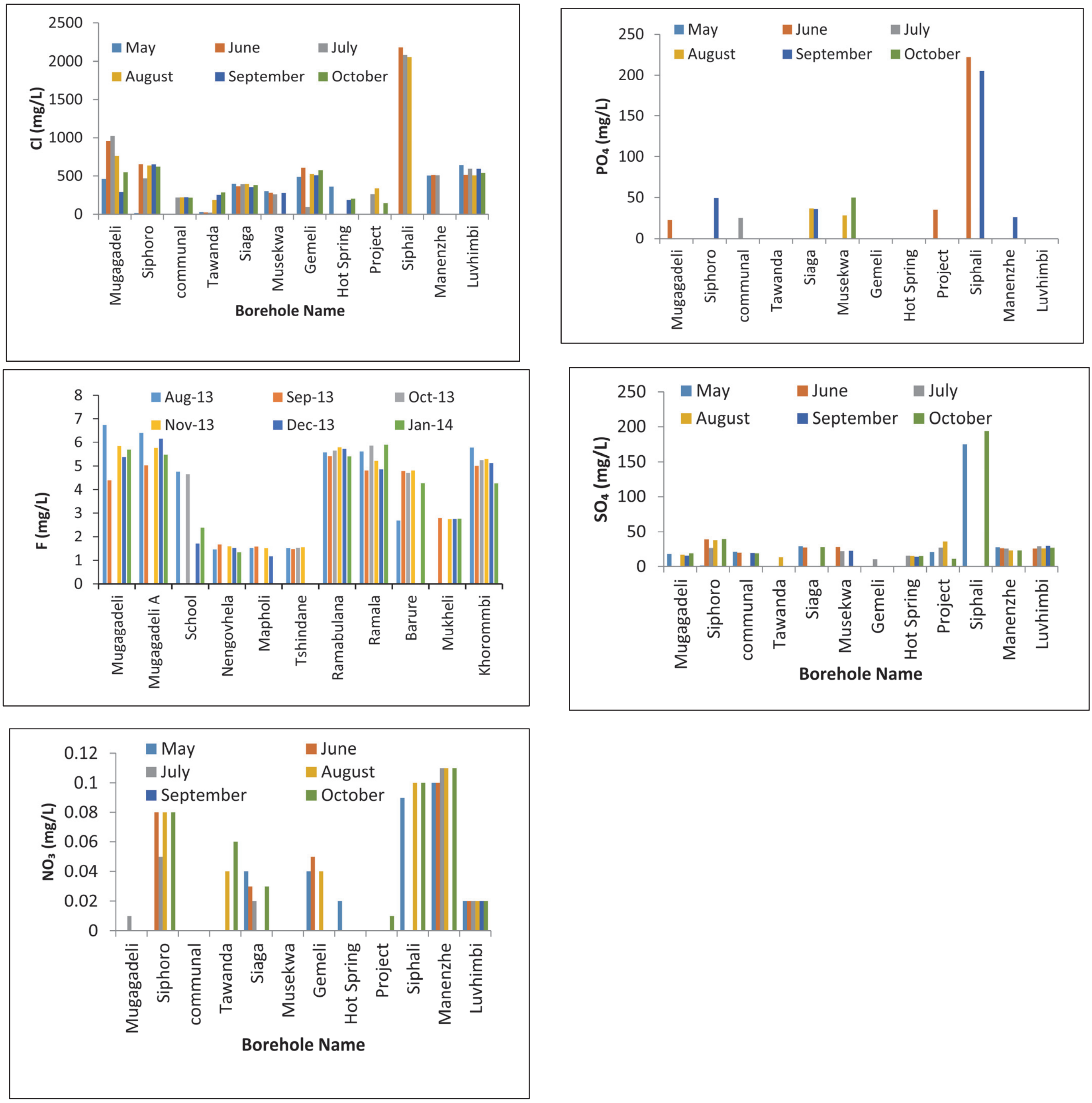


Figure 6.3: Chemical water quality (non-metals)

Figure 6.4 shows concentrations of selected metals for water in sampled boreholes in the period May-October 2012. Copper (Cu), zinc (Zn) and potassium (K) were within water quality guidelines of 0-0.5, <3 and 25 mg/L, respectively (Figure 6.5). Communal, Musekwa and Tawanda boreholes had high iron (Fe) concentrations, which are characterised by a slight salty taste or colour and causes insignificant effects on laundry. Six of the sampled boreholes had magnesium (Mg) concentrations, which exceeded DWAF (1996) guideline of <30 mg/L. Water with Mg concentration >30 mg/L has no health effects, tastes reasonable and it causes slight lathering of soap for both bathing and laundry. Most boreholes had high calcium (Ca) concentrations, which are associated with slight impairement in lathering of soap for bathing and scaling for laundry, though their water is suitable for domestic use without any health effects on human beings. Mugagadeli and Siphali boreholes had sodium (Na) concentrations exceeding the guideline of 100 mg/L in some months. High concentrations of Na are characterized with insignificant aesthetic effects in drinking water, insignificant effects in health and food preparation.

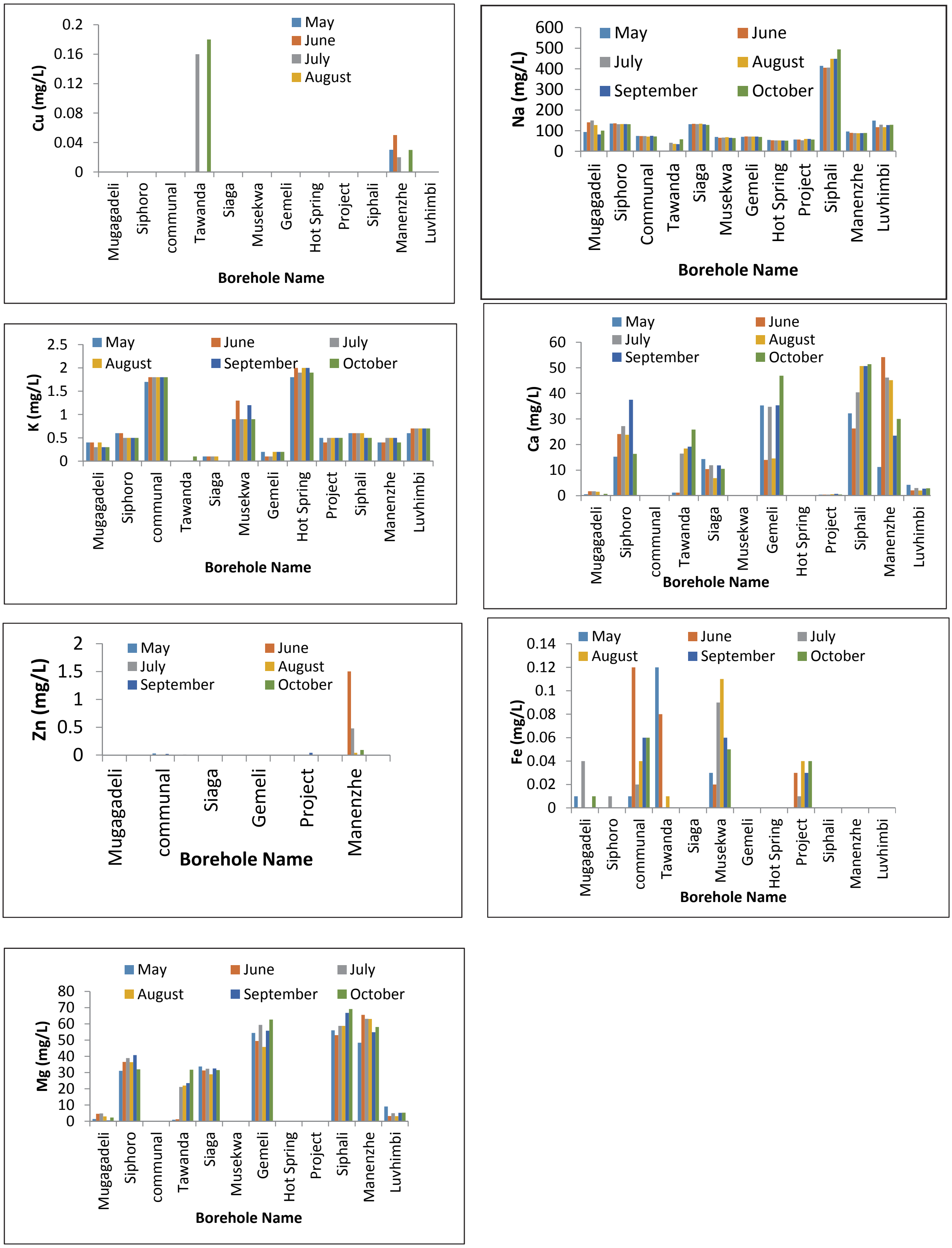


Figure 6.4: Chemical water quality (metals)

6.3 Groundwater operating rules and generalisation

6.3.1 Groundwater operating rules

Derivation of groundwater operating rules was based on results of groundwater storage-reliability analysis and water requirements for domestic water use. The weekly domestic water requirements for Siloam Village (Table 6.3) were estimated from populations projected for 2015, 2020, 2025 and 2030 and the per capita daily water demands. The base population of 2053 for the year 2007 was used in population projections. Equation 6.5 was used to project future population following (DLWS, 2008). DWA (2011) estimated the domestic water requirements for dwellings with yard connections and house connections in Nzhelele area, where the study area falls, to be 101 and 189 l/c/day, respectively. These were used in the current study to represent low (D_1) and high (D_2) demands, respectively.

$$P_{projected} = P_{base} \times (1 + k) \tag{6.5}$$

Where, $P_{projected}$= projected population, P_{base}= base population and k=geometric growth of 0.9504% from DLWS (2008).

Table 6.3: Projected population and water requirements

Year	Projected population	Demand (m^3/week)		Demand (m^3/annum)	
		Low (D_1)	High (D_2)	Low (D_1)	High (D_2)
2015	2231	1577.10	2951.20	82009.20	153462.32
2020	2339	1653.48	3094.13	85980.96	160894.77
2030	2571	1817.52	3401.10	94511.04	176857.57

The groundwater management constraint (GMC), which defines dead/inactive storage level in a manner similar to that of surface water reservoirs/dams (DWA, 2013), was used to determine dead storage for the groundwater reservoir. Dead storage is the volume of water in the aquifer which is not available for supply. GMC is defined as 10-20% of aquifer saturated thickness (DWA, 2013). The dead storage for the GRU in the study area was estimated to have a height of 2.5 m (10% of saturated aquifer thickness). Equations 6.6 to 6.7 were used to derive groundwater operating rules.

$$If\, GS \geq D + DS\; then,\; S = D \tag{6.6}$$

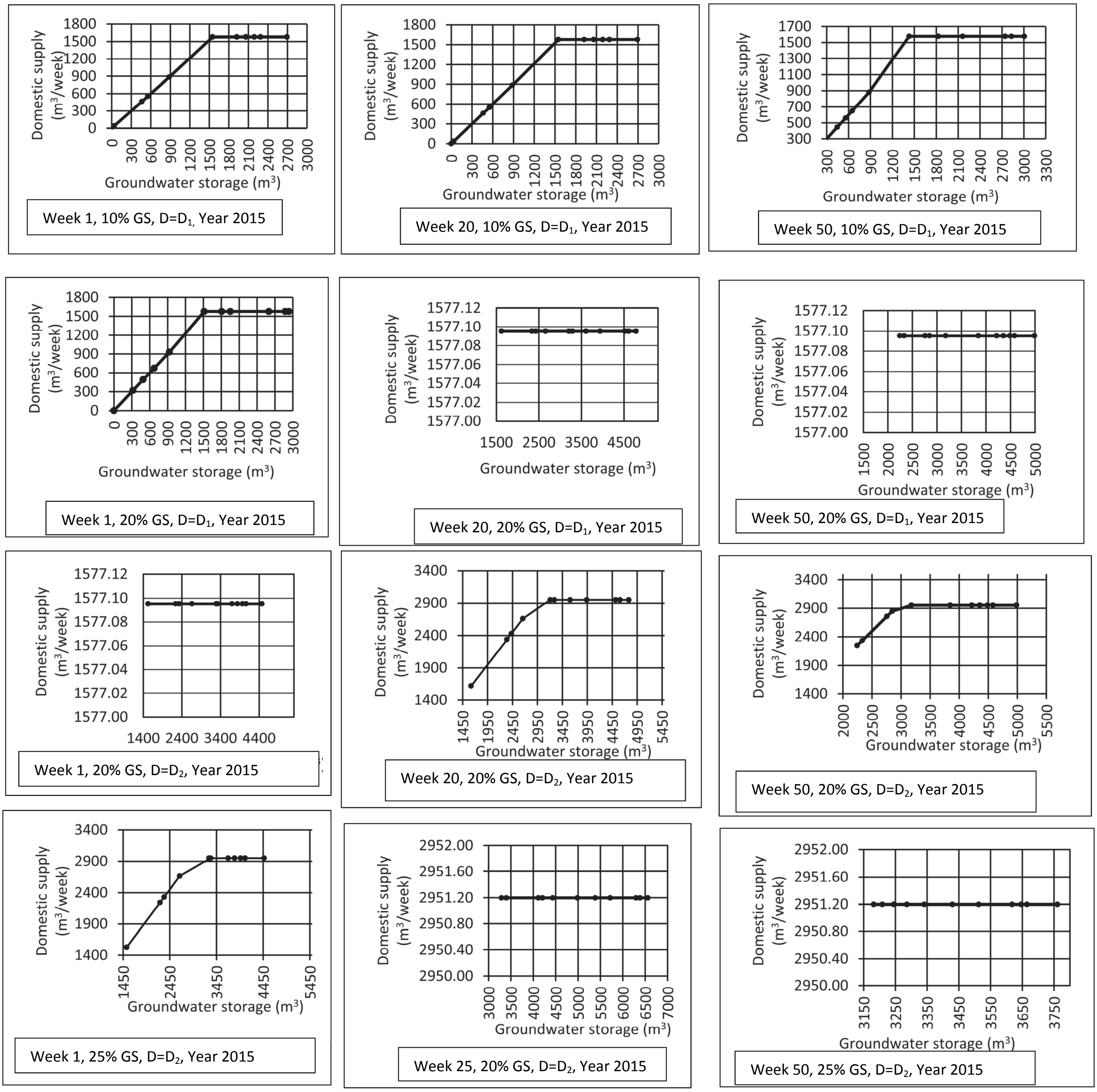
$$If\, GS < D + DS\; then,\; S = GS - DS \tag{6.7}$$

Where *GS* = groundwater storage*, D* = domestic water requirements*, DS*=dead storage*, S* = domestic supply.

Examples of groundwater operating rules derived for weeks 1, 20 and 50 of the year are presented in Figure 6.5. It was envisaged that the operator who will be implementing the groundwater operating rules may not be interested or would not be able to understand the details involved in the derivation of the groundwater storage-reliability curves. Thus, the operating rule curves are presented in a simple graphical form that shows the volume of water to be supplied for domestic purpose at specific GRSLs. This provides simple and user friendly operating rules that can be implemented in rural areas.

The levels of reliability of the storage volumes in the operating rule curves are obtained from the groundwater storage-reliability curves. Since high and low storage volumes are associated with low and high levels of reliability, respectively, the level of reliability decreases as the storage volume increases (see Figure 6.2). This is because high storage volumes are as a result of high groundwater recharge events, which do not occur frequently as compared to low recharge events. In Figures 6.5 to 6.7, the levels of reliability decrease in the order 98, 90, 80, 70, 60, 50, 40, 30, 20,10 and 5% for the plotted storage volumes moving from left to right of the x-axis.

Scenarios for 10, 20, 25, 30, 40, 60, 80 and 100% of GRSLs were run to deduce the influence of percentage GRSLs on derived groundwater operating rules. At 10 and 20% GRSLs (Figure 6.5), available groundwater storage can only partially meet water requirements for 2015 estimated based on 101 l/c/d (D_1) and 189 l/c/d (D_2) at all levels of reliability. However, 20 and 25% GRSLs can fully meet D_1 and D_2, respectively. Figures 6.6 and 6.7 show operating rule curves for future water requirements for the years 2020 and 2030, respectively. Deriving operating rules for future water requirements aids in planning for water resources development and allocation for the future. D_1 was partially met at 20% GRSL, while D_2 was partially met at 20 and 25% GRSLs, respectively, for the year 2020 (Figure 6.6). D_1 for 2020 was fully met at 25% GRSL (Figure 6.6). D_1 for 2030, and D_2 for 2020 and 2030 were met at 30% GRSLs (Figures 6.6 and 6.7). GRSL scenarios which would obviously not meet specific water requirements were not run. For example, D_2 for the year 2015 based on 10% GRSL was not run since it was unable to meet D_1 for the same storage.



Week 1, 10% GS, D=D$_1$, Year 2015

Week 20, 10% GS, D=D$_1$, Year 2015

Week 50, 10% GS, D=D$_1$, Year 2015

Week 1, 20% GS, D=D$_1$, Year 2015

Week 20, 20% GS, D=D$_1$, Year 2015

Week 50, 20% GS, D=D$_1$, Year 2015

Week 1, 20% GS, D=D$_2$, Year 2015

Week 20, 20% GS, D=D$_2$, Year 2015

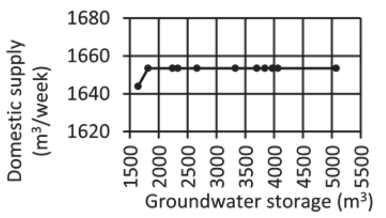
Week 50, 20% GS, D=D$_2$, Year 2015

Week 1, 25% GS, D=D$_2$, Year 2015

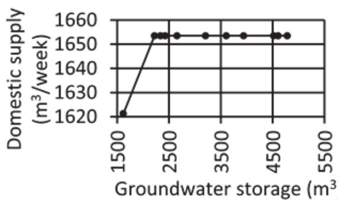
Week 25, 20% GS, D=D$_2$, Year 2015

Week 50, 25% GS, D=D$_2$, Year 2015

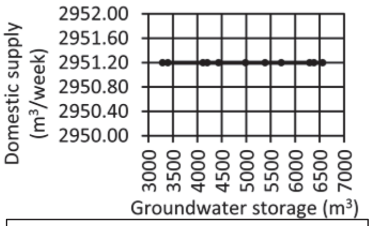
Figure 6.5: Operating rule curves for weeks 1, 20 and 50 for 2015 water requirements



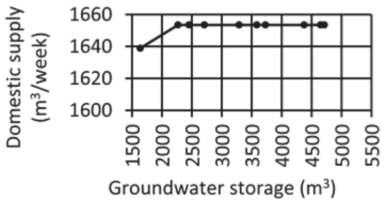
Week 1, 20% GS, D=D_1, Year



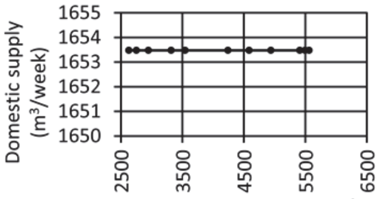
Week 20, 20% GS, D=D_1, Year 2020



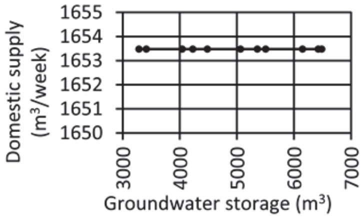
Week 50, 20% GS, D=D_1, Year 2020



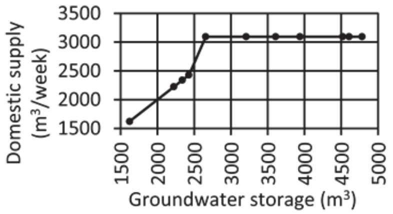
Week 1, 25% GS, D=D_1. Year 2020



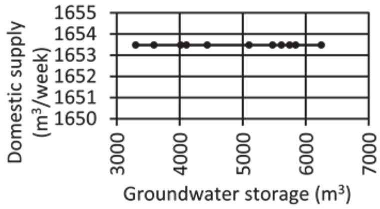
Week 20, 25% GS, D=D_1, Year



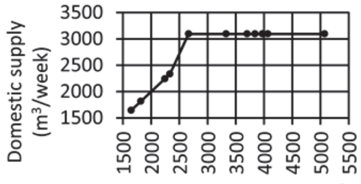
Week 50, 25% GS, D=D_1, Year



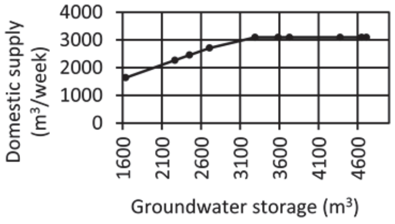
Week 1, 20% GS, D=D_2, Year 2020



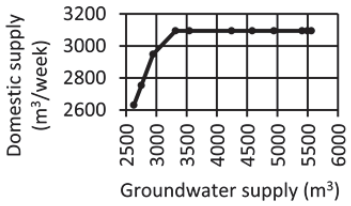
Week 20, 20% GS, D=D_2, Year 2020



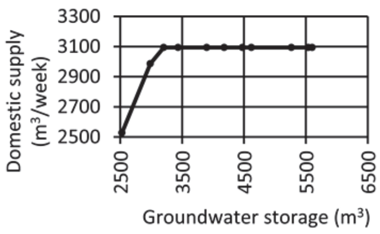
Week 50 20% GS, D=D_2, Year 2020



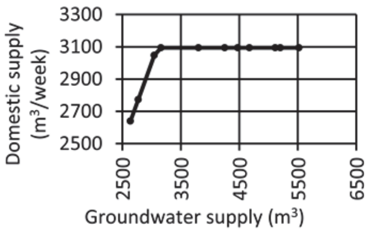
Week 1, 25% GS, D=D_2, Year 2020



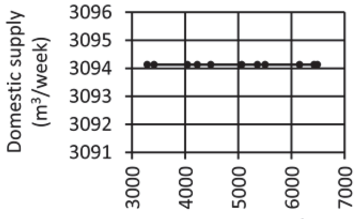
Week 20, 25% GS, D=D_2, Year 2020



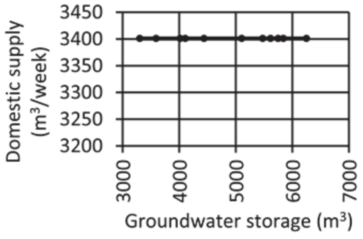
Week 50, 25% GS, D=D_2, Year 2020



Week 1, 30% GS, D=D_2, Year 2020

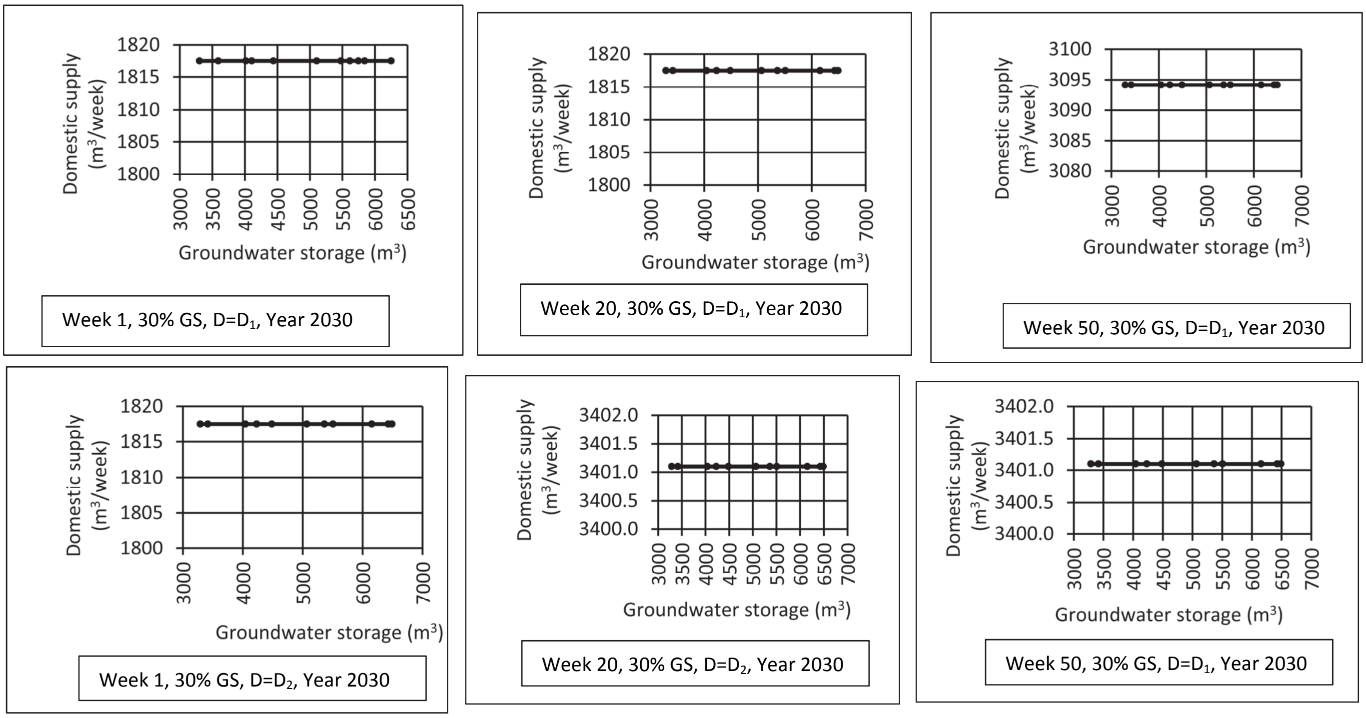


Week 20, 30% GS, D=D_2, Year 2020



Week 50, 30% GS, D=D_2, Year 2020

Figure 6.6: Operating rule curves for weeks 1, 20 and 50 for 2020 water requirements



Week 1, 30% GS, D=D_1, Year 2030

Week 20, 30% GS, D=D_1, Year 2030

Week 50, 30% GS, D=D_1, Year 2030

Week 1, 30% GS, D=D_2, Year 2030

Week 20, 30% GS, D=D_2, Year 2030

Week 50, 30% GS, D=D_1, Year 2030

Figure 6.7: Operating rule curves for weeks 1, 20 and 50 for 2030 water requirements

Table 6.4 summarises the results from Figures 6.5 to 6.7 to show the minimum percentage storages in multiples of 5 that can meet specific water requirements in each scenario. At these % storages, there is adequate groundwater storage to meet the domestic water requirements at all levels of reliability for all scenarios, even if groundwater is considered the only source of water supply in the study area. In addition, the domestic water requirements can be met at the highest reliability/assurance level of 1:100 (99%). Odiyo *et al.* (2015) found that water available in Nzhelele River at Siloam Village cannot meet domestic water requirements at the Department of Water and Sanitation recommended level of assurance of supply of 1:100 (99%). Ndiritu *et al.* (2011a, b) showed that integration of harvested rain water and run-or-river (ROR) supply improves yield and reliability up to 1:25 (96%) for a period of 9 months. Since groundwater can meet domestic demand at the highest recommended reliability levels, its integration with ROR and rainwater would ensure sustainable supply and improve the livelihoods of residents of Siloam Village.

Table 6.4: Minimum percentage storages that can meet specific water requirements

Scenario	Minimum % storage	Water requirement
2015	20	D_1
	25	D_2
2020	25	D_1
	30	D_2
2030	30	D_1
	30	D_2

Values of available groundwater storage volumes at 98% reliability were extracted from groundwater storage-reliability curves and were used to compute water that can be available to supply requirements for 2015, 2020, 2025 and 2030 at 40, 60, 80 and 100% of GRSLs (Table 6.5). This aided in determining the maximum supply from groundwater storage at these GRSLs. Table 6.5 shows that daily available supply ranges from 311.10 to 1072.37 L/c/d and could potentially be met from 40 to 100% GRSLs for weeks 1, 20 and 50, if groundwater is developed. This shows that supply from these GRSLs exceed D_1 and D_2, and hence groundwater is potentially available for other uses such as subsistence farming and construction industry such as brick making and building. This confirms that proper development of groundwater resources will contribute to reduction of poverty and ensure sustainability of livelihoods.

Table 6.5: Available groundwater storage and available supply

Year	Storage level (%)	Available groundwater storage (m^3)			Available supply (L/week)			Available supply (L/c/d)		
		Week 1	Week 20	Week 50	Week 1	Week 20	Week 50	Week 1	Week 20	Week 50
2015	40	5710.46	5598.32	5692.83	5710458.42	5598320.75	5692827.51	365.66	358.48	364.53
	60	9377.74	9153.57	9248.08	9377744.17	9153574.75	9248081.51	600.48	586.13	592.18
	80	12820.97	12708.83	12803.34	12820966.42	12708828.75	12803335.51	820.96	813.78	819.83
	100	15952.02	16747.27	16358.60	15952019.03	15952019.03	16358589.51	1021.45	1072.37	1047.49
2020	40	5710.46	5598.32	5692.83	5710458.42	5598320.75	5692827.51	364.35	357.20	363.23
	60	9377.74	9153.57	9248.08	9377744.17	9153574.75	9248081.51	598.34	584.03	590.06
	80	12820.97	12708.83	12803.34	12820966.42	12708828.75	12803335.51	818.03	810.87	816.90
	100	15952.02	16747.27	16358.59	15952019.03	15952019.03	16358589.51	974.40	1022.98	999.24
2025	40	5710.46	5598.32	5692.83	5710458.42	5598320.75	5692827.51	332.70	326.17	331.67
	60	9377.74	9153.57	9248.08	9377744.17	9153574.75	9248081.51	546.36	533.30	538.81
	80	12820.97	12708.83	12803.34	12820966.42	12708828.75	12803335.51	746.97	740.44	745.94
	100	15952.02	16747.27	16358.59	15952019.03	15952019.03	16358589.51	929.39	975.72	953.08
2030	40	5710.46	5598.32	5692.83	5710458.42	5598320.75	5692827.51	317.33	311.10	316.35
	60	9377.74	9153.57	9248.08	9377744.17	9153574.75	9248081.51	521.12	508.67	513.92
	80	12820.97	12708.83	12803.34	12820966.42	12708828.75	12803335.51	712.47	706.23	711.49
	100	15952.02	15952.02	16358.59	15952019.03	15952019.03	15952019.03	886.46	930.95	909.05

6.3.2 Implications of water quality on implementation of groundwater operating rules

Turbidity and EC values, F, Mg, Ca, Na and PO_4 were higher than the DWAF (1996) guidelines for domestic use in most boreholes throughout the sampling period. Most of these parameters had effects, which include corrosion in laundry, lathering of soap, salty and bitter water. These have no direct impact on human health. Turbidity and fluoride had potential to cause significant health effects. Turbidity values greater than 1 NTU indicate the presence of pathogenic organisms in water. This has been confirmed in a study by Mafenya

(2007), which indicated presence of microorganisms such as faecal coliforms, total coliforms, faecal enterococci, clostridium perfringens and heterotrophic plate counts in groundwater from Siloam Village at levels exceeding DWAF (1996) guidelines for domestic water use. Mudau (2011) reported that counts for total coliform, faecal coliform, faecal streptococci, heterotrophs and *E. coli* in the water samples collected from boreholes in the study area exceeded the DWAF (1996) guidelines for domestic use in most cases. This was linked to possible contamination of groundwater by pit latrines. Mukhumo (2014) also reported presence of total coliforms and *E. coli* in groundwater from Siloam Village which were also linked to possible contamination of groundwater by pit latrines.

Evidence of the effect of excessive fluoride on human health in the study area was reported in a study by Odiyo and Makungo (2012) which showed that most of the residents and school children who use groundwater had mottled teeth as explained earlier. Having recognised the impacts of excessive fluoride on human health in the study area, a number of studies on removal of fluoride have been developed using Siloam Village as a test site. Examples include a study by Gitari *et al.* (2013), which found that modified bentonite clay was able to remove the excess fluoride concentrations to below the WHO water quality guideline and Ologundudu (2016) who reported that modified vermiculite had removal efficiency of 50% of fluoride in groundwater. Once a suitable defluoridation method is fully developed and implemented, the availability of groundwater for domestic supply with minimal health problems would be achieved.

As explained earlier, microbial contamination and excessively high concentrations of fluoride in groundwater make it unsuitable for domestic use. If groundwater is to be fully developed as a source of water supply, treatment against fluorides and microorganisms would be required so that it can be suitable for domestic use. Thus, treatment of groundwater is recommended as part of the interventions with implications on the operating rules for the study area. This should be aimed at reducing fluoride concentrations and turbidity, which provides conducive environment for microbial organisms.

6.3.3 Generalisation of derived groundwater operating rules

The procedure followed in developing groundwater operating rules has been summarised to provide generalised procedure that can be applied to any GRU within a hydrogeologically similar environment (crystalline basement aquifer). Thus, the procedure is limited to crystalline basement aquifer environment. Application in other aquifer types such as coastal or karst aquifers would require prior testing and possible modification of the procedure. The generic procedure is summarised in Figure 6.10 and its brief description is as follows:

1. Determine the existing water uses and their requirements.
2. Delineate a GRU and define its boundaries. Where open flow boundaries exist estimate inflow and/or outflow at these boundaries.
3. Obtain all data which constitute components of groundwater balance in the GRU and compute the groundwater storage.
4. Compute the reliability levels for different groundwater storages using Weibull plotting position (groundwater storage-reliability analysis), and plot graphs to illustrate the groundwater-storage reliability curves.
5. Plot a graph of groundwater storage versus water requirements. This will be the operating rule curve showing the water requirements that can be supplied at different groundwater storage volumes. The portions of the water requirements to be supplied is determined by Equations 6.6 and 6.7.
6. Assess the suitability of groundwater for domestic use and recommend and/or implement appropriate treatment if necessary.

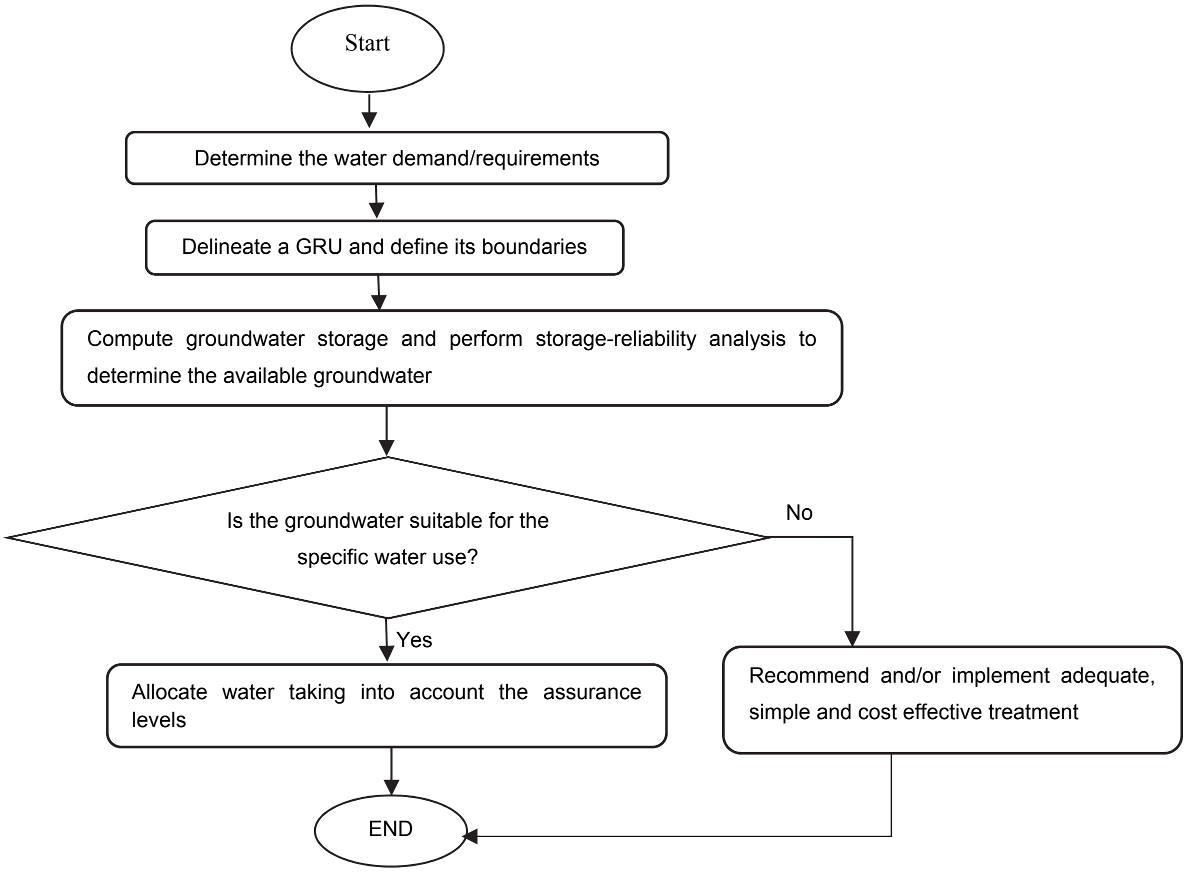


Figure 6.8: Groundwater supply operating framework for typical rural water supply

6.3.4 Data constraints and limitations affecting implementation of the operating rules in rural areas

Lack of adequate and reliable data required for proper assessment of groundwater resources and derivation of groundwater operating rules is a common problem in rural areas of South Africa. This is despite the fact that most rural areas are located in remote and poor rural areas which lack adequate and potable water supply from surface water schemes, and are thus dependent on groundwater. These areas can be categorised as data constrained. Due to this, groundwater development in such areas is very limited since the status of the quantity and quality of groundwater resources is mostly unknown. Most studies shift focus to water resources assessment and development in urban areas where there is reliable data. This exacerbates the problem of data scarcity in rural and remote areas. Thus, most of these areas end up being neglected leading to extreme water scarcity and poverty.

Problems of lack of adequate and reliable data were also encountered in the current study. Data available for the current study was mostly of short periods and had gaps. This led to the use of models to patch and extend the data to enable groundwater storage-reliability analysis and generation of operating rules. Characterisation of the GRU and development of its hydrogeological conceptual model were also based on limited data. This led to uncertainty in the findings of this study. Thus, further work is essential to monitor and acquire more data to reduce uncertainty.

It is important to emphasise that this type of study provides opportunities to unlock further studies and identify areas that require improvement in terms of groundwater resources assessment, development of groundwater operating rules and their implementation. In addition, it provides baseline information that can be used to guide future studies. These may include studies focused on additional and extensive field data collection and monitoring.

Though, the study developed simple and user friendly operating rules that can be implemented in rural areas, their implementation is limited due to lack of appropriate water supply and monitoring infrastructure. This includes monitoring and production boreholes as well as equipment to monitor groundwater levels and quality. It is therefore emphasised that implementation of operating rules by the community would require installation of appropriate monitoring and operating infrastructure. The current study therefore provides guidelines on how reliable and implementable operating rules can be developed for data constrained rural areas and what can be done to facilitate implementation of such operating rules. It is also important to educate the community about the operating rules and their implementation.

7 CONCLUSIONS

Treatment of groundwater aimed at reducing fluoride concentrations and turbidity (providing conducive environment for microbial organisms) is crucial if groundwater is to be considered as a primary source of water supply and should therefore be part of the operating rules for the study area. Groundwater operating rules were generalised by summarising the procedure followed in the development of the operating rules in Siloam Village to allow their application in other areas located in hydrogeologically similar environments (crystalline basement aquifers). Applications in other hydrogeologically different environments (coastal or karst aquifers, for example) will possibly require prior testing and modification of the procedure.

This study used groundwater balance and Weibull plotting position methods in a groundwater storage-reliability analysis approach aimed at deriving groundwater operating rules for a GRU with no groundwater yield data. The approach also involved assessment of the implication of water quality on implementation of groundwater operating rules. Due to lack of continuous long-term data on the components of the groundwater balance, NPR and system identification models were used to patch and/or extend data.

Derived operating rule curves show that groundwater has the potential to supply low domestic water demand from a minimum GRSL of 20% in 2015. This is projected to increase to a minimum GRSL of 25 and 30% in 2020 and 2030, respectively. Operating rules show that high domestic water demand can be met from a minimum GRSL of 25% in 2015, and 30% in 2020 and 2030. Estimated maximum supply from 40, 60, 80 and 100% of GRSL showed that daily available supply ranges exceed water requirements, and hence groundwater is potentially available for other uses such as subsistence farming and construction industry such as brick making and building. This confirmed that proper development of groundwater resources will contribute to reduction of poverty and ensure sustainability of livelihoods in Siloam Village.

Assessment of groundwater quality revealed that high turbid levels, which is an indication of microbial contamination of groundwater from pit latrines and excessive fluoride concentration pose significant health risks to residents of Siloam Village. Thus, treatment of groundwater aimed at reducing fluoride concentrations and turbidity (providing conduce environment for microbial organisms) should be part of the groundwater operating rules for the study area. Groundwater operating rules were generalised by summarising the procedure followed in the development of the operating rules in Siloam Village to allow its application in other areas located in hydrogeologically similar environments. Application in other hydrogeological environments (coastal or karst aquifers, for example) will possibly require prior testing and modification of the procedure.

8 RECOMMENDATIONS

Practical implementation of the operating rules would require installation of appropriate water supply and monitoring infrastructure. This includes monitoring and production boreholes as well as equipment to monitor groundwater levels. There is currently one community and a few private boreholes for domestic water supply in the study area. Monitoring of groundwater levels will also be useful in updating the developed operating rules. There should be continuous monitoring of components of the groundwater balance, which include rainfall, evapotranspiration, soil moisture, runoff, groundwater abstractions and groundwater levels to allow for future updating of the developed operating rules. Detailed geophysical investigation, borehole logging and pump testing should be carried out to enhance the hydrogeological conceptual model for the study area. In addition, fracture network analysis and exploration drilling are required for detailed understanding of the groundwater systems in the study area.

Groundwater quality should also be monitored continuously to enable generation of its trend that will aid in ensuring suitability for domestic use or necessary interventions. Further testing and/or application of defluoridation methods that have been developed using Siloam Village as a test site is essential. This will aid in identification and development of a suitable defluoridation method to enhance supply of groundwater with minimal health problems.

Since the generalised procedure for developing groundwater operating rules is limited to crystalline basement aquifer environment, its application in other aquifer types such as coastal or karst aquifers require prior testing and possible modification.

9 LIST OF REFERENCES

Adams, S., Titus, R. and Xu, Y. (2004) *Groundwater recharge assessment of the basement aquifers of central Namaqualand*, WRC Report No. 1093/1/04, Water Research Commission, Pretoria, South Africa, 179 pp.

Adamowski, K. (1985) Non parametric kernel estimation of flood frequencies, *Water Resources Research*, vol. 21(11), pp. 1585-1590.

Adamowski, K. (1987) Nonparametric techniques for analysis of hydrologic events, Proceedings of the Rome Symposium, IAHS Publication no. 164, pp. 56-76.

Aguado, E., Remson, I., Pikul, M.F., Thomas, W.A. (1974). Optimal pumping for aquifer dewatering, *J. Hyd. Div.*, Amer. Soc. Civil Engr., vol 100 (HY7), pp. 869-877.

Ali, A. (1998) Nonparametric Spatial Rainfall Characterization Using Adaptive Kernel Estimator, *Journal of Geographic Information and Decision Analysis*, vol. 2(2), pp. 34-43.

Allen R.G., Pereira, L.S., Rae, D. and Smith, M. (1998) Crop Evapotranspiration (guidelines for computing crop water requirements*), FAO Irrigation and Drainage Paper No. 56,* 300pp.

Anderson, M.P. and Woessner, W.W. (1992) Applied groundwater modelling simulation of flow and advective transport, Academic Press, 381 pp.

Arrey, I.A. (2012). Modelling groundwater recharge in the unsaturated zone recharge in Siloam Village, honours mini dissertation, University of Venda, 83 pp.

Barker, O., Brandl, G., Callaghan, C.C. and Van der Neut, M. (2006) The Soutpansberg and Waterberg Groups and Blouberg formation, Chapter 14, In. Johnson, C. R., Anhaeusser, and R.J Thomas (Eds), *The Geology of South Africa,* Geological Society of South Africa and the Council for Geoscience, pp. 301-318.

Basson, M.S., Allen, R.B., Pegram, G.G.S. and Van Rooyen, J.A. (1994). *Probabilistic management of water resource and hydropower systems*, Water Resources Publications, USA, 434 pp.

Bejaichund, M., Kijko, A. and Durrheim, R. (2009) Seismotectonic models for South Africa: Synthesis of Geoscientific Information, problems, and the way forward, *Seismological Research Letters*, vol. 80, pp. 65-33.

Borrocu, G. (2014) *Handbook of engineering hydrology: fundamentals and applications*, In: Eslamian, S. (Ed) Groundwater hydrology: Saturation zone, pp. 221-250

Brandl, G. (1981) The geology of the Messina area, Explanation sheet, Geological Survey South Africa, 2230 (Messina), 35 pp.

Brandl, G. (2003) Geology, In: Macdonald I.A.W., Gaigher, I. and Gaigher, R., A first synthesis of the Environmental, Biological and cultural assets of the Soutpansberg, Lajuma Synthesis workshop, http://www.soutpansberg.com/workshop/pdf_files/geology.pdf

Bumby, A.J., Eriksson, P. G., Van der Merwe, R., Steyn, G. L. (2002) A half-graben setting for the Proterozoic Soutpansberg Group (South Africa): evidence from the Blouberg area, *Sedimentary Geology*, vol. 147 (1-2), pp. 37-56.

Chinoda, G., Matura, N., Moyce, W. and Owen, R. 2009. Baseline Report on the Geology of the Limpopo Basin Area, a contribution to the Challenge Program on Water and Food Project 17 "Integrated Water Resource Management for Improved Rural Livelihoods: Managing risk, mitigating drought and improving water productivity in the water scarce Limpopo Basin". WaterNet Working Paper 7. WaterNet, Harare, 44 pp.

Cleveland, W.S. (1979) Robust locally weighted regression and smoothing, *Journal of the American Statistical Association*, vol. 74(368), pp. 829-836.

Cleveland, W.S. and Devlin S.J. (1988) Locally weighted regression: an approach to regression analysis by local fitting, *Journal of the American Statistical Association*, vol. 83 (403), pp. 596- 610.

Conrad, J. and Van der Voort, I. (2000) Classification of groundwater resources under the National Water Act of South Africa, In: Sililo et al. (Eds) Groundwater: Past achievements and Future Challenges, Balkema Publishers, Netherlands, pp. 901-905.

Conrad, J., and Van der Voort, I. (1999). A GIS based experimental methodology to determine the utilisable potential of South African aquifers. WRC Report No. 840/1/99, Water Research Commission, Pretoria.

Das Gupta, A. and Onta, P.R. (1994). Groundwater management models for Asian developing countries, *Water Resources Development*, vol. 10(4), pp.457-474.

Das Gupta, A., Nobi, N. and Paudyai, G.N. (1992). Modelling a multi-aquifer system for groundwater management, Gayer, J., Starosolszky, O. and Maksimovic, O. (Eds) Hydrocomp '92, Water Resources Research Center (VITUKI), Hungary, pp. 41-48.

Das Gupta, A., Nobi, N. and Paudyai, G.N. (1996). Ground-water management model for an extensive multiaquifer and an application, *Groundwater*, vol. 34(2), pp. 349-357.

Das, A. and Datta, B. (2001). Application of optimisation techniques in groundwater quantity and quality management, *Sadhana*, vol. 26, Part 4, August 2001, pp. 293-316.

Datta B. and Hakrishna V. (2004). Optimization Applications in Water Resources Systems Engineering, Directions, Indian Institute of technology Kanpur, Special Issue on Optimization, vol. 6(3), pp. 57-64.

Dennis S.R. (2007) Development of a decision tool for groundwater management, PhD thesis, Faculty of Natural and Agricultural Sciences, Institute of Groundwater Studies, University of Free State, Bloemfontein, 198 pp.

Dennis, I., Van Tonder, G.J. and Riemann, K., (2002). Risk based decision tool for managing and protecting groundwater resources, WRC Report No 969/1/01, Water Research Commission, Pretoria, South Africa.

Department of Water Affairs (DWA), 2010. Resource Directed Measures: Reserve Determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua catchment: Ecological Water Requirements Study – Main Report: Outeniqua Reserve Study (K10-K50, K60G). Report No. RDM/K000/02/CON/0907.

Dippenaar, M.A. (2008) Characterisation of some fractured rock aquifers in Limpopo Province, South Africa: review and case study, MSc thesis, University of Pretoria, South Africa.

Dippenaar, M.A., Witthüser, K.T. and Van Rooy, J.L. (2009) Groundwater occurrence in Basement aquifers in Limpopo Province, South Africa: model-setting-scenario approach, Environmental Earth Sciences, vol. 59, pp. 459-464.

Dreizin, Y.C. and Haimes, Y.Y. (1977). A hierachy of response functions for groundwater management, *Water Resources Research*, vol. 13(1), pp.78-86.

DLWS (2008) Bulk infrastructure feasibility planning, Project LPR00@ Nzhelele RWS, 2nd draft Vhembe District Municipality, Limpopo Province.

DWA (2010) Groundwater strategy 2010, Department of Water Affairs, Pretoria, 64 pp.

DWA (2011) Development of a reconciliation strategy for all towns in The Northern Region, First order reconciliation strategy for Nzhelele Regional Water Supply Scheme, Contract WP 9711, Department of Water Affairs, South Africa, 12 pp.

DWA (2013). Feasibility study for augmentation of the Lusikisiki Regional Water Supply Scheme: assessment of augmentation from groundwater, DWA Report no. PWMA 12/T60/00/3811, Department of Water Affairs, South Africa.

DWAF (1996) South African water quality guidelines, vol. 1: Domestic water use, 2nd Edition, Pretoria, 216pp.

DWAF (2004c). Urgent need for augmentation of the Umgeni system, DWAF, Pretoria, 25pp.

DWAF, (2004a) Groundwater management strategy, Department of Water Affairs and Forestry, Pretoria, 14 pp.

DWAF, (2004a). National Water Resource Strategy, 1st Edition, Department of Water Affairs and Forestry, Pretoria, 150 pp.

DWAF, (2004b). Approaches to quantifying groundwater, Department of Water Affairs and Forestry, Pretoria, 43 pp.

DWAF, (2004b). Groundwater management strategy, Department of Water Affairs and Forestry, Pretoria, 14 pp.

DWAF, (2006). Groundwater resource assessment: Task 1D, groundwater quantification, Department of Water Affairs and Forestry, Pretoria, 106 pp.

DWAF, Department of health and Water Research Commission (1998) Quality of domestic water supplies, vol. 1: Assessment guide, WRC Report TT 101/98, 104 pp.

Elshamy, M.E. (2008) Assessing the hydrological performance of the Nile forecast system in long term simulations, *Nile Water Science & Engineering Magazine*, vol.1, pp. 22-36.

FAO, (2003) Groundwater management-the search for practical approaches, Water Report 25, Rome, Italy.

Fox, J. (2002) Nonparametric Regression http://cran.r-project.org/doc/contrib/Fox-Companion/appendix-nonparametric-regression.pdf, accessed 27/02/2014.

Fox, J. (2004) Nonparametric Regression, McMaster University, Canada, http://socserv.mcmaster.ca/jfox/Nonparametric-regression.pdf, accessed on 03/01/2014.

Franke O.L., Reilly E.L. and Bennet G.D. (1987) Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems-an introduction, Chapter B5, Techniques of water-resources investigations of the United States Geological Survey , United States Geological Survey, Washington, 15 pp.

Gallagher, M. and Leach, L. (2010). The Groundwater Operational Management Package (GWOMP), Groundwater 2010, Canberra, www.groundwater2010.com/documents/GallagherMark.pdf.

Gitari, W.M., Ngulube, T., Masindi, V. and Gumbo, J.R. (2013) Defluoridation of groundwater using Fe3+-modified bentonite clay: optimization of adsorption conditions, *Desalination and Water Treatment*, pp. 1-13.

Gorelick, S.M. (1983). A review of distributed groundwater management modeling method, *Water Resources Research*, vol. 19(2), pp. 305-319.

Guggino, E., Rossi, G. and Hendricks, D.W. (1983). *Operation of complex water systems: operation, planning and analysis of already developed water systems*, Springer Publishers, 504 pp.

Haddad, O.B. and Mariño, M.A. (2010). Optimum operation of wells in coastal aquifers, Proceedings of the ICE - Water Management, vol. 164(3), pp. 135-146.

Hallaji, K. and Yazicigil, H. (1996) Optimal management of a coastal aquifer in southern Turkey, *J. Water Res. Planning Manage. Div., Am. Soc. Civ. Eng, vol.* 122, pp. 233-244.

Harpaz, Y. and Schwarz, J. (1967). Operating a limestone aquifer as a reservoir for a water supply system, *Hydrological Sciences Journal*, vol. 12 (1), pp. 78-90.

Harrold, T.I, Sharma*,* A. *and* Sheather S.J. *(*2003*)* A nonparametric model for stochastic generation of daily rainfall amounts*, Water Resources Research, vol. 39, pp. 1-12.*

Harrold, T.I. (2002) Stochastic generation of daily rainfall for catchment water management studies, PhD Thesis, University of New South Wales, Sydney, Australia, 198 pp.

Holland, M. (2011) Hydrogeological characterisation of crystalline basement aquifers within the Limpopo Province, South Africa, University of Pretoria, Pretoria, South Africa, 163 pp.

Holland, M. (2012) Evaluation of factors influencing transmissivity in fractured hard-rock aquifers of the Limpopo Province, *Water SA*, vol. 38 (3), pp. 379-390.

Hyndman R.J. and Koehler A.B. (2006) Another look at measures of forecast accuracy*, International Journal of Forecast*, vol. 22, pp. 679-88.

Jackson, J.M. (2007) Hydrogeology and groundwater flow model, Central catchment of Bribie Island, South of Queensland, MSc Thesis, Queensland University of Technology, Queensland, Australia.

Johnson, L.E. (1993). Water supply systems adjustment to drought, In: The Colorado Internet Center for Environmental Problem Solving (ed.), Improving the environmental problem-solving process: Lessons from the 1988-?? California drought, CU Conflict Resolution Consortium, Boulder.

Kebede, S. (2013) *Groundwater in Ethiopia, Number and opportunities*, Springer Hydrogeology, 283 pp.

Kalf, F.R.P. and Woolley, D.R. (2005). Applicability and methodology of determining sustainable yield in groundwater systems, *Hydrogeol J*, vol. 13, pp. 295-312.

Kalra, A. and Ahmad, S. (2011) Evaluating changes and estimating seasonal precipitation for Colorado River Basin using stochastic nonparametric disaggregation technique, *Water Resources Research,* vol. 47, pp. 1-26.

Khan, L.R. and Mawdsley, J.A. (1988) Reliable yield of unconfined aquifers, *Hydrological Sciences Journal*, vol. 33(2), pp. 151-171.

Knoop, W.T. and Walker, B.H. (1985). Interactions of woody herbaceous vegetation in a southern African savannah, *Journal of Ecology*, vol. 73(1), pp. 235-253.

Kruseman, G.P. and de Ridder, N.A. (2000) Analysis and evaluation of pumping test data, 2nd Ed, *International Institute for Land Reclamation and Improvement*, Publication no. 47, pp. 372.

Labatiuk, C. (1985) A nonparametric approach to flood frequency analysis, MSc Thesis, University of Ottawa.

Lall, U. (1995) Nonparametric function estimation: recent hydrologic applications, Reviews of Geophysics, US National Report 1991-1994, pp. 1093-1102.

Lall, U., Rajagopalan, B. and Tarboton, D.G. (1996) A nonparametric wet/dry spell model for resampling daily precipitation, *Water Resources Research*, vol. 32 (9), pp. 2803-2823.

Lin, S.-C. WU, R.-S. and Wang M.-H. (2003). A hybrid model coupling analytic simulation with optimization for rule-curve based operation in tandem multireservoir systems, *Transactions on Ecology and the Environment*, vol. 61, pp. 75-83.

Lindner, W., Lindner, K., and Karadi, G. (1988). Optimal groundwater management of large scale aquifers, *Water Resources Bulletin*, vol. 24 (1), pp. 27-33.

Lynch, S.D. (2003) Development of a raster database of annual, monthly and daily rainfall for Southern Africa, WRC Report No. 1156/1/04, Water Research Commission, Pretoria, South Africa, 78 pp.

Mafamadi, M.A. (2012). Decision support system for groundwater dependent rural areas: a case study of Siloam Village, honours mini dissertation, University of Venda, 91 pp.

Mafenya, H., (2007) A microbial assessment of potable water source such as ground and surface water in Siloam Village, Limpopo Province of South Africa, H*onours research dissertation*, University of Venda, South Africa, 39pp.

Mahajan G. (2008). Evaluation and development of groundwater, AHP Publishing, 317 pp.

Mahajan G. (2009). Groundwater surveys and investigation, AHP Publishing, 560 pp.

Makungo, R. (2009). An operating strategy for run-of-river abstraction for typical rural water supply schemes using Siloam Villages as a case study, Masters Dissertation, University of Venda, 101 pp.

Makungo, R., Odiyo, J.O., Ndiritu, J.G., Mwaka, B. (2010) Rainfall runoff modelling approach for ungauged Catchments, *Journal of Physics and Chemistry of the Earth*, vol. 35, pp 596-607.

Mason, R. (1973) The Limpopo Mobile Belt, Southern Africa, *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences,* vol. 273, pp. 463-485.

McDowell, R.J. (2010) Assessing sustainable yield of aquifers as part of the Georgia comprehensive statewide water management plan, GSA Denver Annual Meeting, Geological Society of America *Abstracts with Programs*, vol. 42, No. 5, 490 pp..

McMahon, T.A. and Mein, R.G. (1978). *Reservoir capacity and yield*, Amsterdam: Elsevier Publishers, 213pp.

McMahon, T.A., Pegram, G.G.S., Vogel, R.M. and Peel, M.C. (2007a). Revisiting reservoir storage-yield relationships using a global streamflow database, Advances in Water Resources, vol. 30, pp. 1858-1872.

McMahon, T.A., and Pegram, G.G.S., Vogel, R.M. and Peel, M.C. (2007b). Review of Gould-Dincer reservoir storage-yield-reliability estimates, Advances in Water Resources vol. 30, pp. 1873-1882.

McPhee, J. and Yeh, W.W-G. (2004). Multiobjective optimization for sustainable groundwater management in semiarid regions, *Journal of Water Resources Planning and Management*, vol. 130(6), pp. 490-497.

Meyer, R. (2002) Guidelines for the monitoring and management of groundwater resources in rural water supply schemes, Water Research Commission Report no. 861/1/02a, 55 pp.

Monirul, I.M. and Kanungoe, P. (2005). Natural recharge to sustainable yield in the Barind aquifer: a tool in preparing effective management plan of groundwater resources, *Water Science and Technology*, vol. 52(12), pp. 251-258.

Mohamed, L., Sultan, M., Ahmed, M., Zaki, A., Saucki, W., Soliman, F.., Yan, E., Elkadiri, R. and Abouelmagd, A. (2015) Structural Controls on groundwater flow in basement terrains: geophysical, remote sensing, and field investigations in Sinai, *Surveys in Geophysics*, DOI 10.1007/s10712-015-9331-5

Morel, E.H. and Wikramaratna, R.S. (1982) Numerical modelling of groundwater flow in regional aquifers dissected by dykes, *Hydrological Sciences Journal*, vol. 27(1), pp. 63-77.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., and Veith, T. (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, *Transactions of the American Society of Agricultural and Biological Engineers,* vol. 50 (3), pp. 885-900.

Mudau, T.C. (2011) Effects of pit latrines location on groundwater quality of Nzhelele Villages within Limpopo Province, South Africa, H*onours research dissertation*, University of Venda, South Africa.

Mukhumo, V. (2014) Investigating suitability of groundwater for domestic use and impact of pit latrines on groundwater in Siloam Village, H*onours research dissertation*, University of Venda, South Africa, 60 pp.

Murray, R., Baker, K., Ravenscroft, P., Musekiwa, C. and Dennis R. (2012). A groundwater-planning toolkit for the main Karoo basin: Identifying and quantifying groundwater-development options incorporating the concept of well field yields and aquifer firm yields, *Water SA*, vol. 38(3), pp. 407-416.

Nagy, I.V., Asante-Duah, K., Zsuffa, I. (2002*). Hydrological dimensioning and operation of reservoirs: practical design concepts and principles*, Kluwer Publishers, Dordrecht, 225 pp.

Ndiritu, J.G., Odiyo, J.O., Makungo, R., Ntuli, C. and Mwaka, B. (2011a) Yield-reliability analysis for rural domestic water supply from combined rainwater harvesting and run-of-river abstraction, *Hydrological Sciences Journal*, vol. 56(2), pp.238-248.

Ndiritu, J.G., Odiyo, J.O., Makungo, R., Ntuli, C. and Mwaka, B. (2011b). Incorporating hydrological reliability in rural rainwater harvesting and run-of-river supply, *Risk in Water Resources Management,* IAHS Publication no 347.

Njanike, J.T. (2001). Investigations to determine the long-term sustainable yield of the Karoo aquifer and the sustained availability of groundwater for small-scale irrigation projects, in Dendera Area, Kwekwe District, Zimbabwe Master of Science thesis, Rhodes University, Grahamstown, South Africa, 144 pp.

Nyabeze, P.K, Venter, J.S., Olivier, J. and Motlakeng T.R. (2010) Characterization of the thermal aquifer associated with the Siloam hot spring in Limpopo, South Africa, Proceedings of the 3rd IASTED African Conference, Water Resource Management, Gaborone, Botswana.

Nyabeze, P.K., Gwavava, O., Olivier, J., Chirenje E. and Sekiba, M. (2011a) Geophysical characteristics of a shallow aquifer associated with a hot spring in the Limpopo Province, South Africa: results for the Siloam hot spring, Geosynthesis 2011 Conference and Exhibition, Cape Town International Convention Centre, South Africa.

Nyabeze, P.K., Gwavava, O., Olivier, J. Chirenje E. and Sekiba, M. (2011b) Geophysical characteristics of aquifers associated with thermal springs in Limpopo, South Africa. International Groundwater Conference, Pretoria, South Africa, 123 pp.

Obiero, J.P.O., Hassan, M.A., Gumbe, L.O. M. (2011) Modelling of streamflow of a catchment in Kenya, *Journal of Water Resource and Protection*, vol. 3, pp. 667-677.

Odiyo, J.O. and Makungo, R. (2012) Fluoride concentrations in groundwater and impact on human health in Siloam Village, Limpopo Province, South Africa, Water SA, vol. 38(5), pp. 731-736.

Odiyo, J.O., Makungo, R, Ndiritu, J., Mwaka, B. and Ntuli, C. (2015) Yield-reliability analysis and operating rules for run-of-river abstractions for typical rural water supply: Siloam Village case study, *Water SA*, vol. 41, pp. 375-381.

Ökten, S. and Yacigizil, H. (2005). Investigation of safe and sustainable yields for the Sandy Complex Aquifer System in the Ergene River Basin, Thrace Region, Turkey Turkish, *Journal of Earth Sciences*, vol. 14, pp. 209-226.

Olagundudu (2016) Defluoridation of groundwater using vermiculite modified with hexadecyl trimethlyammonium: A case study of Siloam Village, Limpopo Province of South Africa, Masters dissertation, University of Venda, South Africa, 112 pp.

Peralta, R.C., Ashgari, K. and Shulstad, R. (1991). SECTRA for economical optimal sustained groundwater yield planning, *Journal of Irrigation Drainage Engineering*, Amer. Soc. Civil Engr., vol. 117(1), pp. 5-24.

Pietersen, K.C. (2004). A decision-making framework for groundwater management in arid zones (with a case study in Namaqualand), PhD. thesis, University of the Western Cape

Pietersen, K.C. (2006). Multiple criteria decision analysis (MCDA): A tool to support sustainable management of groundwater resources in South Africa, *Water SA*, vol. 32(2), pp.119-128.

Rajagopalan, B. and Lall, U. (1999) A k-nearest-neighbor simulator for daily precipitation and other weather variables, *Water Resources Research*, vol. 35 (10), pp. 3089-3101.

Rathjens, H. and Oppelt, N. (2012) SWAT model calibration of a grid-based setup, *Advances in Geosciences*, vol. 32, 55-61.

Ratnayka, D.D., Brandt, M.J. and Johnson, M. (2009). *Water Supply*, Butterworth-Heinemann Publishers, 6th Edition, Britain, 711 pp.

Ravenscroft, P. and Murray, R. (2004a) A framework for groundwater management of community water supply, toolkit for water services: number 1.1, Department of Water Affairs and Forestry, Pretoria, 35 pp.

Ravenscroft, P. and Murray, R. (2004b) Implementing a rural groundwater management system, a step-by-step guide, toolkit for water services: number 1.2, Department of Water Affairs and Forestry, Pretoria, 25 pp.

Reilly, T.E. (2001) System and boundary conceptualization in groundwater flow simulation, Techniques of water resources investigations of the United States Geological Survey, Book 3, Applications of Hydraulics, Chapter B8, U.S. Department of the Interior and U.S. Geological Survey, 29 pp.

Renard, P., Glenz, D. and Mejias, M. (2009) Understanding diagnostic plots for well-test interpretation, *Hydrogeology Journal*, vol. 17, pp. 589-600

Rugumayo, E. (2001). Reservoir capacity yield reliability analysis, People and Systems for Water, Sanitation and Health, 27th WEDC Conference, Lusaka, Zambia.

Sarmadian, F. and Mehrjardi, R.T. (2008) Modeling of some soil properties using artificial neural network and multivariate regression in Gorgan Province, North of Iran, *Global Journal of Environmental Research*, vol. 2 (1), pp. 30-35.

Sechi, G.M., and Sulis, A. (2009). Water system management through a mixed optimizations simulation approach, *Journal of Water Resources Planning and Management*, vol. 135(3), pp. 160-170.

Sefelnasr, A.M. (2007) Development of groundwater flow model for water resources management in the development areas of the western desert, Egypt, PhD dissertation, Martin Luther University Halle-Wittenberg.

Shamir, U. and Bear, J. (1984). Optimal annual operation of a coastal aquifer, *Water Resources Research*, vol. 20 (4), pp. 435-444.

Shamsudin, S. and Hashim, N., (2002) Rainfall runoff simulation using Mike11 NAM, *Journal of Civil Engineering*, vol.5(2), pp. 1-13.

Sharma, A. and U. Lall, (1999) A nonparametric approach to daily rainfall simulation. *Mathematics and Computers in Simulation*, vol. 48, pp. 367-371.

Sharma, S.P. and Baranwal, V.C. (2005) Delineation of groundwater-bearing fracture zones in a hard rock area integrating very low frequency electromagnetic and resistivity data, *Journal of Applied Geophysics*, vol. 57, pp. 155-166.

Singh, J., Knapp, H. V., and Demissie, M. (2004) Hydrologic Modeling of the Iroquois River Watershed Using HSPF and SWAT, Illinois State Water Survey Contract Report 2004-08, Illinois Department of Natural Resources and Illinois State Geological Survey, 24 pp.

Singh, M., Kijko, A. and Durrheim, A. (2009) Seismotectonic Models for South Africa: Synthesis of geoscientific information, problems, and the way forward, *Seismological Research Letter*, vol. 80(1), pp. 71-80.

Singhal, V. and Goyal, R. (2011) GIS based methodology for groundwater flow estimation across the boundary of the study area in groundwater flow modeling, *Journal of Water Resource and Protection*, vol. 3, pp. 824-831.

Singhal, B.B.S. and Gupta R.P. (2010) *Applied hydrogeology of fractured rocks*, 2nd Ed, Springer, 408 pp.

Sophocleous, M. (1997). Managing water resources systems: Why “safe yield” is not sustainable *Groundwater*, vol. 35 (4), pp. 561

Sophocleous, M. (1998a). On the elusive concept of safe yield and the response of interconnected stream-aquifer systems to development, Chapter 2, In: Sophocleous, M. (Ed), Perspectives on Sustainable Development of Water Resources in Kansas, Kansas Geological Survey, Bulletin 239, pp. 61-85.

Sophocleous, M. (1998b). Concluding comments on managing water-resources systems: why “safe yield” is not sustainable, Chapter 10, In: Sophocleous, M (Ed), Perspectives on Sustainable Development of Water Resources in Kansas, Kansas Geological Survey, Bulletin 239, pp.211-213.

Sophocleous, M. (2000). From safe yield to sustainable development of water resources-the Kansas experience, *Journal of Hydrology*, vol. 235, pp. 27-43.

Srikanthan, R., Harrold, T.I., Sharma, A. and McMahon T.A. (2005) comparison of two approaches for generation of daily rainfall data, *Stochastic Environmental Research and Risk Assessment*, vol. 19 (3), pp 215-226.

Uddameri, V. and Honnungar V. (2007) Interpreting sustainable yield of an aquifer using a fuzzy framework, *Environmental Geology*, vol. 51, pp. 911-919.

Van Liew, M.W., Veith, T.L., Bosch, D.D. and Arnold, J.G. (2007) Suitability of SWAT for the conservation effects assessment project: A comparison on USDA-ARS experimental watersheds, *Journal of Hydrologic Engineering,* vol.12 (2), pp. 173-189.

Van Tonder G., Bardenhagen, I., Riemann, K., Van Bosch, J, Dzanga, P. and Xu, Y.(2002 Manual on pumping test analysis in fractured rock aquifers , WRC Report No III6/1/02, Water Research Commission, Pretoria South Africa, 228 pp.

Van Tonder, G.J., Botha, J.F., Chiang, W.-H., Kunstmann, H. and Xu, Y. (2001) Estimation of the sustainable yields of boreholes in fractured rock formations, *Journal of Hydrology*, vol. 241, pp. 70-90.

Van Tonder, G.T., Kunstmann, H., Xu, Y. and Fourie, F. (2000) Estimation of the sustainable yield of a borehole including boundary information, drawdown derivatives and uncertainty propagation, *Calibration and Reliability in Groundwater Modelling* (Proceedings of the ModelCARE 99 Conference held at Zurich, Switzerland, September 1999), IAHS Publ. no. 265, pp. 367-373.

Van Wyk, E., Van Tonder, G.J., and Vermeulen, D. (2012) Characteristics of local groundwater recharge cycles in South African semi-arid hard rock terrains: Rainfall-groundwater interaction, Water SA, vol. 38(5), pp. 747-754.

Votruba, L. and Broza, V. (1989). *Water management in reservoirs,* Developments in Water Science, vol. 33. Elsevier, Amsterdam, 444 pp.

Wanakule, N., Mays, L.W. and Lasdon, L.S. (1986). Optimal management of large-scale aquifers: methodology and applications. *Water Resour. Res, vol.* 22, pp. 447-465.

Willis, R. (1983) A unified approach to regional groundwater management, In: Rosenshein, J.S. and Bennett, G.D. (Eds), Groundwater Hydraulics, Water Resource Monograph Series, American Geophysical Union, Washington, 416 p.

Willis, R. and Liu, P. (1984) Optimisation model for groundwater planning. *J. Water Resour. Planning Manage. Div., Am. Soc. Civ. Eng, vol.* 110, pp. 333–347.

Wilson, A.S. (2005) Hydrogeology, conceptual model and groundwater flow within alluvial aquifers of the Tenthill and Ma Ma Catchments, Lokyer Valley, Queensland, MSc Thesis, Queensland University of Technology, Queensland, Australia, 141 pp.

Witthüser, K., Cobbing, J., Titus, R., Holand, M. and Pietersen, K. (2009a). Strategy and guideline development for national groundwater planning requirements, A proposed GRA3 methodology, DWA Report Number PRSA 000/00/11609/7, Department of Water Affairs, Pretoria, South Africa.

Witthüser, K., Cobbing, J., Rian, T., Pietersen, K. and Fourie, F. (2009b). A framework for groundwater resources assessment (GRA) methodologies and a proposal for GRA3, Proceedings of the Groundwater Conference, Somerset West, Cape Town, South Africa.

Wright, E. P. (1992) *The hydrogeology of crystalline basement aquifers in Africa*, Wright, E.P. and Burgess, W.G. (Eds), Hydrogeology of Crystalline Basement Aquifers in Africa, Geological Society Special Publication no. 66, pp 1-27.

Wright, K.A. and Xu, Y. (2000). A water balance approach to the sustainable management of groundwater in South Africa, *Water SA*, vol. 26 (2), pp. 167-170.

Wurbs, R.A. (1991). Optimization of multi-purpose reservoir system operation: A review of modelling and analysis techniques, US Army Corps of Engineers, Hydrologic Engineering Centre, 83 pp.

Wurbs, R.A. (1993). Reservoir system simulation and optimization models, *Journal of Water Resources Planning and Management*, vol. 119(4), pp. 455-472.

Wurbs, R.A. (1996). *Modelling and analysis of reservoir system operations*, Prentice-Hall, Upper Saddle River, NJ, 356 pp.

Wurbs, R.A. (2005). Modeling river/reservoir system management, water allocation, and supply reliability, *Journal of Hydrology*, vol. 300, pp. 100-113.

Yates E.B., Feeney, M.B. and Rosenberg, L.I. (2005). Seaside groundwater basin: An update on water resource conditions, Monterey Peninsula Water Management District, 58 pp.

Yazdanian, A. and Peralta, R.C. (1986). Sustained-yield groundwater-pumping strategy by goal programming, *Groundwater*, vol. 24(2), pp. 157-165.

Zhang, L. and Kennedy, C. (2006). Determination of sustainable yield in urban groundwater systems: Beijing, China, *Journal of Hydrologic Engineering*, vol. 11(1), pp. 21-28.

Zhou, Y.X. (2009). A critical review of groundwater budget myth, safe yield and sustainability, *Journal of Hydrology*, vol. 370, pp. 207-213.

APPENDIX A: GROUNDWATER STORAGE-RELIABILITY AT SELECTED GRSLs

	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY											
WEEK	5	10	20	25	30	40	50	60	70	80	90	98
1	1944.96	1938.75	1911.42	1883.17	1846.70	1832.29	1802.70	1744.57	1719.02	1700.45	1683.44	1637.62
2	1951.20	1926.01	1905.43	1891.32	1883.27	1845.91	1807.26	1745.54	1726.04	1700.84	1686.33	1612.12
3	1955.60	1919.07	1891.23	1881.08	1875.06	1843.39	1807.85	1746.02	1721.17	1691.23	1672.29	1616.38
4	1953.55	1909.99	1902.94	1876.88	1848.15	1838.65	1820.61	1735.40	1713.68	1699.18	1691.35	1616.11
5	1953.38	1905.74	1888.06	1882.12	1876.64	1847.07	1822.63	1737.05	1718.19	1698.27	1684.36	1595.20
6	1950.13	1900.40	1899.76	1855.81	1875.98	1853.03	1840.42	1732.26	1720.80	1696.55	1649.39	1587.45
7	1926.74	1906.50	1894.90	1880.65	1869.86	1839.57	1828.07	1733.93	1707.72	1695.10	1658.00	1582.36
8	1916.67	1675.77	1946.78	1806.28	1873.30	1846.44	1915.86	1744.66	1665.77	1695.14	1647.84	1581.78
9	1938.63	1911.29	1896.38	1873.45	1851.44	1841.60	1825.33	1743.44	1698.03	1687.20	1645.90	1579.70
10	1936.86	1909.06	1897.35	1863.50	1852.09	1835.03	1810.15	1742.16	1701.15	1676.40	1693.86	1662.16
11	1933.15	1896.26	1888.72	1856.40	1849.07	1819.98	1805.11	1737.00	1704.21	1691.11	1647.80	1620.23
12	1928.13	1891.69	1887.56	1862.53	1848.01	1816.61	1794.53	1745.93	1717.01	1702.64	1636.67	1653.27
13	1929.03	1890.43	1880.42	1865.57	1849.94	1840.64	1796.30	1754.75	1726.26	1700.38	1620.21	1664.35
14	1926.94	1904.67	1882.99	1867.46	1846.03	1837.72	1815.85	1738.13	1725.15	1686.32	1640.46	1592.19
15	1916.11	1894.11	1877.64	1858.80	1850.52	1839.58	1820.56	1750.62	1728.26	1688.21	1652.54	1568.63
16	1897.38	1888.86	1884.40	1869.79	1857.41	1832.08	1781.11	1749.71	1720.83	1704.24	1668.28	1603.40
17	1894.22	1892.69	1865.40	1869.74	1862.42	1846.20	1786.02	1759.25	1701.60	1681.98	1675.07	1623.62
18	1916.65	1887.11	1865.80	1864.75	1856.78	1837.14	1771.70	1741.40	1716.03	1694.52	1650.84	1608.40
19	1920.54	1886.45	1870.83	1867.26	1861.43	1837.60	1772.27	1738.17	1715.45	1684.57	1637.61	1615.43
20	1920.92	1885.14	1870.72	1861.77	1857.61	1843.79	1806.47	1739.94	1706.83	1697.87	1655.33	1626.41
21	1920.33	1872.85	1873.66	1861.48	1841.97	1847.93	1842.25	1746.46	1704.83	1702.15	1677.45	1662.01
22	1919.28	1874.48	1865.88	1862.71	1854.78	1839.11	1780.06	1752.93	1707.80	1698.14	1669.50	1618.32
23	1919.00	1874.65	1871.61	1860.09	1855.51	1848.82	1784.77	1750.94	1710.19	1704.29	1690.28	1612.24
24	1918.33	1882.32	1872.95	1862.00	1859.77	1838.27	1785.28	1749.34	1720.05	1705.60	1681.58	1675.20
25	1917.39	1878.91	1871.74	1868.26	1861.38	1818.16	1785.03	1749.48	1727.59	1711.03	1696.67	1685.71
26	1910.86	1885.05	1873.12	1868.41	1853.31	1833.90	1804.94	1751.20	1745.24	1728.53	1697.80	1671.98
27	1913.15	1898.02	1883.15	1869.4	1862.72	1848.55	1805.79	1754.31	1749.25	1731.13	1699.41	1653.60
28	1916.99	1903.90	1889.06	1882.63	1865.55	1847.12	1781.15	1751.14	1735.98	1726.67	1702.53	1660.56
29	1915.17	1896.42	1889.61	1884.12	1876.25	1846.05	1788.88	1747.43	1727.90	1716.05	1701.84	1656.13
30	1910.60	1904.52	1887.23	1881.89	1879.55	1849.74	1791.09	1746.52	1733.13	1710.98	1702.83	1653.19
31	1908.66	1895.19	1886.51	1885.14	1878.74	1853.19	1788.01	1752.38	1741.12	1709.96	1702.79	1667.72
32	1915.46	1909.07	1885.57	1879.96	1876.49	1857.21	1791.06	1756.86	1746.33	1710.49	1703.22	1669.65
33	1933.55	1914.91	1882.81	1874.6	1865.60	1833.91	1787.83	1753.24	1738.75	1710.18	1701.83	1665.34
34	1947.31	1910.32	1888.87	1871.34	1866.96	1830.19	1783.45	1749.77	1735.38	1713.15	1706.34	1672.81
35	1945.81	1906.37	1877.73	1871.13	1868.14	1816.46	1786.86	1746.16	1737.71	1714.63	1701.54	1674.73
36	1950.24	1917.27	1878.73	1870.23	1862.01	1810.24	1791.03	1750.14	1733.45	1713.49	1702.45	1646.98
37	1953.17	1924.96	1880.21	1879.64	1866.75	1806.36	1785.30	1760.44	1732.81	1716.02	1702.60	1645.59
38	1953.55	1932.61	1891.11	1883.65	1871.86	1805.02	1786.03	1762.94	1736.91	1718.62	1700.36	1636.99
39	1949.83	1934.34	1895.50	1892.26	1866.17	1839.15	1783.36	1774.23	1734.04	1720.93	1702.41	1659.74
40	1949.29	1932.62	1910.43	1889.5	1873.79	1854.70	1782.44	1759.29	1732.74	1721.22	1703.40	1663.97
41	1942.17	1928.96	1912.68	1895.44	1884.07	1859.23	1781.44	1744.71	1734.04	1725.31	1703.74	1663.51
42	1948.42	1932.82	1914.20	1896.79	1886.23	1857.88	1784.72	1743.46	1736.47	1725.06	1705.58	1663.75
43	1930.87	1921.55	1905.33	1898.44	1894.33	1856.25	1798.07	1742.35	1733.63	1722.25	1708.36	1656.80
44	1934.32	1922.02	1901.67	1898.64	1884.17	1857.65	1801.77	1736.13	1726.38	1716.54	1703.65	1662.62
45	1938.83	1922.54	1905.23	1896.22	1888.62	1855.61	1814.53	1741.88	1723.86	1715.09	1706.72	1682.20
46	1942.68	1927.82	1919.27	1901.66	1893.00	1858.02	1797.24	1736.92	1723.15	1711.63	1702.63	1683.94
47	1948.05	1941.56	1927.17	1898.98	1891.97	1852.85	1803.01	1731.24	1724.93	1713.16	1685.61	1679.38
48	1953.82	1940.90	1929.91	1903.02	1898.28	1854.05	1795.93	1733.52	1723.38	1714.55	1693.35	1665.50
49	1952.13	1938.86	1928.49	1899.98	1866.95	1834.20	1793.95	1736.55	1722.49	1709.07	1695.41	1653.01
50	1952.09	1934.52	1925.79	1897.74	1867.76	1834.48	1794.50	1739.50	1716.59	1707.51	1696.07	1635.86
51	1951.76	1934.00	1923.27	1897.38	1865.79	1832.33	1815.85	1741.64	1717.36	1701.70	1682.85	1653.43
52	1948.59	1935.18	1918.14	1897.19	1871.09	1834.60	1814.27	1739.45	1716.80	1701.64	1673.12	1638.81

Appendix A1: Groundwater storage-reliability at 10% GRSL

	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY										
WEEK	5	10	20	25	30	40	50	60	70	80	90	98
1	3914.23	3889.92	3883.47	3877.50	3822.85	3766.34	3755.49	3693.41	3668.18	3605.39	3489.14	3456.74
2	3902.40	3831.22	3817.64	3782.64	3769.10	3766.54	3693.64	3614.51	3491.09	3453.16	3452.07	3423.66
3	3911.19	3838.12	3812.80	3762.17	3761.34	3750.12	3695.28	3615.70	3492.03	3444.75	3442.33	3426.53
4	3907.11	3808.28	3806.40	3753.76	3749.09	3696.29	3681.64	3641.22	3470.80	3432.75	3427.36	3426.55
5	3906.76	3806.86	3791.03	3764.23	3758.50	3753.28	3697.32	3645.26	3474.10	3468.51	3436.37	3422.64
6	3900.25	3800.81	3799.51	3759.28	3751.96	3730.95	3711.61	3654.47	3470.85	3454.24	3441.61	3422.87
7	3853.48	3811.62	3795.77	3761.30	3756.72	3739.73	3709.18	3656.14	3467.87	3422.59	3415.44	3403.36
8	3879.83	3821.05	3813.81	3760.72	3746.61	3704.39	3675.81	3612.57	3484.56	3404.45	3398.71	3398.18
9	3877.25	3809.25	3806.55	3746.91	3725.87	3702.88	3683.63	3650.66	3486.88	3401.91	3396.05	3392.78
10	3873.72	3800.10	3794.70	3727.00	3708.72	3704.19	3666.90	3620.30	3484.31	3406.31	3402.29	3397.30
11	3866.31	3788.26	3788.00	3712.79	3702.00	3698.15	3669.86	3610.22	3474.00	3410.38	3408.43	3405.56
12	3856.26	3783.38	3781.39	3723.48	3703.74	3696.02	3663.96	3628.15	3469.04	3434.03	3423.17	3405.29
13	3858.07	3780.85	3762.70	3728.54	3699.89	3699.77	3681.28	3610.61	3461.52	3452.52	3442.04	3441.10
14	3853.88	3831.47	3809.34	3776.32	3774.67	3765.99	3743.27	3702.14	3692.05	3675.44	3568.35	3535.44
15	3832.22	3827.73	3788.22	3784.64	3772.37	3755.29	3731.23	3713.60	3701.05	3679.16	3548.93	3530.04
16	3794.76	3787.79	3777.73	3776.04	3775.25	3768.80	3742.18	3719.56	3714.81	3664.16	3531.16	3510.83
17	3808.00	3788.43	3785.37	3774.40	3739.48	3734.18	3730.81	3714.83	3707.12	3669.86	3528.87	3518.49
18	3833.31	3808.77	3774.22	3773.77	3760.59	3731.59	3729.74	3717.91	3713.55	3674.28	3529.19	3518.24
19	3841.08	3799.15	3772.91	3759.28	3747.59	3741.66	3738.57	3725.12	3722.86	3675.20	3533.84	3508.20
20	3841.83	3778.98	3770.28	3760.50	3751.46	3741.44	3725.95	3717.19	3715.23	3687.57	3558.29	3548.28
21	3840.66	3762.02	3760.28	3747.33	3745.71	3732.54	3726.36	3713.82	3698.99	3684.50	3547.15	3525.47
22	3838.56	3774.50	3748.96	3747.23	3746.78	3731.75	3728.02	3712.15	3709.57	3678.22	3540.69	3515.93
23	3837.99	3772.21	3749.29	3745.94	3743.39	3743.21	3728.35	3712.53	3711.03	3697.65	3542.08	3533.75
24	3836.66	3770.88	3764.65	3756.07	3746.39	3745.90	3743.70	3720.54	3719.55	3676.54	3553.09	3536.91
25	3834.77	3765.75	3757.83	3756.36	3747.50	3743.48	3740.68	3734.58	3722.76	3636.31	3547.43	3543.16
26	3821.72	3770.19	3770.11	3761.72	3747.70	3746.25	3742.27	3735.78	3706.62	3667.80	3565.54	3552.63
27	3826.30	3811.31	3796.04	3777.44	3774.16	3766.30	3763.13	3735.04	3725.44	3697.10	3561.59	3542.66
28	3833.97	3830.72	3807.79	3789.86	3782.23	3778.12	3769.51	3738.54	3731.10	3694.24	3550.73	3514.78
29	3830.35	3810.12	3792.84	3788.74	3783.95	3779.23	3778.60	3766.03	3752.50	3692.10	3564.69	3545.61
30	3821.21	3820.87	3809.05	3787.00	3781.66	3774.46	3768.97	3762.02	3759.10	3699.49	3575.82	3528.37
31	3817.32	3810.04	3790.38	3788.49	3776.76	3773.02	3772.28	3765.89	3757.48	3706.39	3560.25	3526.46
32	3830.92	3827.95	3818.13	3785.44	3776.92	3771.13	3763.04	3753.41	3752.99	3714.42	3553.67	3541.19
33	3867.10	3846.85	3829.82	3788.27	3785.19	3765.63	3753.60	3747.46	3731.20	3667.81	3566.37	3543.91
34	3894.61	3859.59	3820.65	3792.32	3779.96	3777.75	3759.20	3737.03	3733.92	3660.37	3565.19	3554.67
35	3867.27	3755.23	3632.91	3799.37	3740.49	3781.71	3736.27	3755.45	3891.62	3349.45	3812.75	3429.96
36	3900.48	3834.55	3818.44	3757.47	3740.71	3724.01	3620.49	3600.44	3587.32	3582.05	3500.27	3466.89
37	3906.34	3849.92	3849.02	3760.42	3760.00	3733.50	3612.72	3610.58	3605.94	3570.59	3520.88	3465.63
38	3907.10	3865.23	3851.59	3782.22	3781.05	3743.73	3610.05	3593.82	3590.06	3572.07	3525.88	3473.82
39	3899.67	3868.67	3849.45	3791.00	3789.44	3732.33	3678.30	3633.04	3600.70	3566.73	3548.45	3468.08
40	3898.59	3865.23	3849.75	3820.87	3792.37	3747.57	3709.40	3692.29	3617.29	3564.89	3518.58	3465.48
41	3884.33	3857.91	3844.60	3825.35	3801.63	3768.15	3718.45	3675.80	3649.40	3562.89	3489.43	3468.07
42	3896.84	3865.64	3853.40	3828.41	3810.76	3772.46	3715.76	3661.06	3652.66	3569.44	3486.92	3472.95
43	3861.74	3843.10	3831.45	3810.65	3797.50	3788.67	3712.49	3654.59	3641.02	3596.13	3484.71	3467.25
44	3868.65	3844.05	3815.98	3803.34	3798.85	3768.34	3715.31	3657.42	3649.35	3603.54	3472.26	3452.76
45	3877.67	3845.07	3820.95	3810.47	3803.89	3777.24	3711.22	3661.96	3656.73	3629.07	3483.77	3447.73
46	3885.36	3855.65	3850.80	3838.54	3821.11	3785.99	3716.05	3667.08	3643.37	3594.47	3473.84	3446.30
47	3896.09	3883.12	3864.43	3854.35	3817.27	3783.94	3705.70	3669.21	3638.64	3606.02	3462.48	3449.87
48	3907.65	3881.80	3880.71	3859.83	3814.86	3796.57	3708.10	3668.66	3641.28	3591.87	3467.05	3446.75
49	3904.27	3877.73	3875.12	3856.98	3815.45	3733.90	3668.41	3628.42	3621.28	3587.91	3473.09	3444.99
50	3904.17	3869.04	3867.34	3851.58	3819.18	3735.51	3668.96	3634.63	3618.18	3589.00	3478.99	3433.17
51	3903.53	3868.00	3854.07	3846.54	3827.08	3731.59	3664.66	3650.47	3642.70	3631.70	3483.27	3434.73
52	3916.85	3897.18	3892.45	3870.37	3852.90	3836.28	3835.17	3821.8	3794.37	3779.65	3742.18	3688.93

Appendix A2: Groundwater storage-reliability data at 20% GRSL

WEEK	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY											
	5	10	20	25	30	40	50	60	70	80	90	98
1	4862.40	4846.88	4778.56	4707.92	4616.76	4580.71	4506.74	4361.43	4297.56	4251.12	4208.60	4094.06
2	4878.00	4815.02	4763.58	4728.31	4708.17	4614.77	4534.07	4363.86	4315.09	4252.11	4215.82	4030.30
3	4888.99	4797.69	4728.08	4702.71	4687.65	4608.48	4518.14	4365.04	4302.92	4228.06	4180.73	4040.96
4	4883.89	4774.97	4757.34	4692.2	4605.10	4579.87	4551.52	4338.50	4284.20	4247.94	4228.37	4040.28
5	4883.46	4764.34	4720.16	4698.13	4686.36	4617.69	4556.58	4342.62	4295.46	4245.66	4210.91	3988.00
6	4875.32	4757.95	4741.55	4699.26	4663.69	4632.57	4568.09	4338.56	4302.01	4241.38	4149.28	3968.64
7	4816.85	4766.26	4737.24	4699.1	4674.66	4598.93	4570.17	4334.83	4269.30	4237.75	4145.00	3955.90
8	4849.79	4767.26	4616.10	4706.28	4700.89	4581.53	4515.71	4318.87	4247.73	4164.43	4119.60	3954.44
9	4846.56	4758.19	4628.59	4710.05	4683.63	4579.98	4604.53	4310.03	4245.07	4075.10	4132.60	3949.24
10	4842.15	4740.83	4630.23	4722.82	4658.75	4565.32	4579.45	4323.83	4252.87	4122.06	4128.22	4155.40
11	4832.88	4734.99	4622.68	4721.79	4651.58	4549.96	4535.04	4322.46	4250.12	4050.57	4119.49	4115.77
12	4820.32	4734.59	4620.03	4718.91	4654.35	4541.53	4565.81	4320.39	4250.74	4133.17	4091.67	4138.65
13	4822.58	4726.88	4624.86	4701.05	4660.68	4601.59	4599.83	4317.31	4222.76	4160.88	4050.52	4192.52
14	4817.35	4718.34	4610.47	4679.09	4627.67	4578.94	4539.63	4322.80	4298.41	4107.90	4101.16	3980.47
15	4784.66	4715.46	4602.45	4694.11	4598.95	4664.03	4587.98	4320.66	4299.51	4131.35	4145.35	3921.58
16	4711.00	4720.06	4601.27	4719.06	4571.80	4674.46	4598.37	4314.67	4299.95	4170.69	4260.59	4008.51
17	4663.51	4718.00	4599.14	4633.9	4550.72	4674.35	4587.33	4300.78	4301.81	4187.67	4204.96	4059.05
18	4641.94	4717.21	4592.85	4620.8	4700.74	4662.18	4593.14	4290.08	4300.65	4127.09	4239.29	4070.19
19	4305.60	4430.68	4038.57	4312.69	4377.55	4211.41	4716.14	4569.45	4863.14	4529.29	4653.58	4385.25
20	4267.08	4435.36	4066.02	4288.94	4407.94	4239.10	4700.62	4552.99	4880.94	4585.51	4646.48	4516.18
21	4262.09	4433.94	4155.02	4279.45	4406.83	4269.59	4665.67	4556.97	4912.59	4354.90	4642.27	4605.62
22	4259.88	4425.86	4245.35	4269.51	4394.91	4309.83	4684.04	4530.12	4919.44	4382.32	4636.96	4597.77
23	4261.28	4417.19	4275.47	4225.69	4377.36	4353.96	4660.43	4559.61	4887.25	4427.60	4640.66	4638.79
24	4269.44	4421.14	4263.99	4284.52	4365.34	4373.34	4679.62	4595.68	4860.32	4441.36	4635.51	4713.60
25	4277.58	4428.95	4224.42	4282.32	4366.29	4373.71	4670.66	4545.39	4867.36	4462.58	4630.28	4695.45
26	4275.69	4440.78	4236.52	4179.94	4364.53	4367.31	4596.31	4590.20	4874.31	4525.58	4633.27	4671.03
27	4269.67	4451.99	4246.30	4133.99	4349.71	4347.00	4538.05	4745.06	4873.90	4532.26	4630.83	4621.37
28	4263.87	4392.45	4238.89	4151.4	4328.50	4316.67	4532.15	4792.46	4884.48	4377.84	4617.80	4663.88
29	4254.59	4312.28	4225.76	4140.31	4302.80	4319.74	4524.15	4729.93	4893.34	4455.86	4600.07	4741.06
30	4257.07	4266.81	4219.66	4132.97	4277.44	4335.18	4495.15	4698.88	4885.57	4477.71	4633.30	4776.09
31	4288.58	4256.97	4224.80	4169.31	4266.28	4352.80	4450.31	4737.97	4890.41	4470.03	4601.13	4762.55
32	4263.45	4258.05	4238.27	4174.12	4266.80	4369.02	4400.20	4784.94	4893.47	4480.91	4581.38	4772.66
33	4274.49	4239.78	4254.56	4163.34	4275.45	4359.35	4366.61	4833.87	4881.01	4483.36	4572.41	4787.27
34	4283.41	4252.62	4265.84	4182.03	4282.87	4358.98	4350.79	4872.47	4868.27	4464.02	4556.28	4775.81
35	4864.52	4765.93	4694.31	4677.82	4670.34	4541.14	4467.14	4365.41	4344.27	4286.58	4253.84	4186.82
36	4875.59	4773.05	4655.02	4675.58	4675.89	4583.68	4477.57	4360.16	4333.62	4283.72	4256.13	4117.45
37	4885.82	4811.28	4700.00	4666.66	4681.90	4699.11	4463.24	4348.44	4332.03	4283.83	4256.49	4113.97
38	4883.87	4831.53	4726.31	4709.13	4679.66	4512.56	4465.08	4407.36	4342.28	4296.55	4250.91	4092.47
39	4874.59	4835.84	4738.75	4665.42	4679.30	4500.87	4458.41	4444.50	4362.60	4302.32	4256.04	4180.12
40	4873.23	4841.23	4740.46	4640.14	4684.46	4521.62	4453.14	4456.11	4366.93	4308.28	4258.50	4286.36
41	4855.42	4838.66	4738.61	4734.64	4699.96	4561.75	4451.91	4442.38	4361.78	4313.27	4259.34	4323.29
42	4871.04	4832.05	4785.51	4741.97	4710.19	4644.70	4461.80	4358.65	4341.18	4312.64	4263.96	4159.38
43	4746.10	4827.18	4779.99	4746.88	4720.71	4643.32	4495.17	4355.89	4340.77	4307.78	4270.90	4141.99
44	4729.05	4827.37	4769.97	4748.56	4741.38	4644.14	4504.43	4354.30	4328.83	4302.13	4259.13	4156.56
45	4721.56	4827.19	4772.35	4740.54	4746.61	4646.47	4497.44	4354.71	4303.09	4300.28	4264.91	4205.50
46	4699.09	4826.26	4776.39	4732.49	4736.21	4654.45	4493.09	4342.30	4276.10	4304.18	4256.58	4209.85
47	4870.11	4853.91	4817.93	4747.45	4729.92	4632.12	4507.53	4328.11	4312.33	4282.90	4214.03	4198.46
48	4921.25	4850.89	4828.23	4745.71	4757.56	4635.12	4489.83	4333.81	4327.32	4291.60	4163.75	4246.95
49	4929.71	4843.90	4831.04	4749.94	4535.52	4662.13	4484.89	4341.36	4307.88	4294.41	4132.51	4257.27
50	4912.83	4834.17	4822.69	4744.34	4543.29	4608.31	4475.30	4348.74	4276.74	4291.22	4089.65	4249.67
51	4879.41	4835.00	4808.17	4743.44	4664.48	4580.83	4539.62	4354.09	4293.41	4254.25	4207.12	4133.58
52	4871.48	4837.96	4795.35	4742.97	4677.72	4586.50	4535.67	4348.62	4292.00	4254.09	4182.80	4267.52

Appendix A3: Groundwater storage-reliability data at 25% GRSL

	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY											
WEEK	5	10	20	25	30	40	50	60	70	80	90	98
1	5834.88	5816.25	5734.27	5649.50	5540.11	5496.86	5408.09	5233.71	5157.07	5101.34	5050.32	4912.87
2	5853.60	5778.02	5716.30	5673.97	5649.81	5537.72	5440.89	5236.63	5178.11	5102.53	5058.99	4836.36
3	5866.79	5757.18	5423.55	5669.49	5643.25	5530.17	5421.77	5238.05	5167.13	5105.99	5068.05	4849.15
4	5860.66	5729.96	5708.81	5630.64	5526.12	5495.84	5461.83	5206.20	5141.04	5097.53	5074.04	4848.34
5	5860.15	5646.35	5749.87	5629.91	5545.98	5485.27	5467.89	5206.61	5154.56	5090.53	5053.09	4785.61
6	5850.38	5709.54	5689.86	5639.11	5596.43	5559.09	5481.71	5206.27	5162.41	5089.66	4979.13	4762.36
7	5780.22	5571.81	5693.66	5717.43	5563.77	5507.61	5484.21	5238.32	5133.89	5092.12	4974.00	4747.08
8	5819.75	5509.91	5692.91	5747.57	5556.59	5539.31	5497.84	5268.19	5087.24	5098.07	4943.51	4745.33
9	5815.88	5709.83	5652.06	5551.99	5619.91	5495.97	5524.80	5172.03	5094.08	5078.23	4890.12	4739.09
10	5810.58	5715.53	5689.00	5590.50	5556.28	5496.35	5430.44	5226.47	5103.44	5068.85	4986.49	4946.48
11	5799.46	5707.97	5681.99	5581.90	5547.22	5408.83	5445.58	5216.51	5100.15	5112.64	4938.92	4860.68
12	5784.39	5678.10	5681.50	5585.22	5544.04	5442.22	5458.41	5203.56	5100.88	5151.04	4966.38	4959.80
13	5787.10	5675.66	5672.26	5592.81	5549.83	5415.91	5437.55	5192.28	5067.31	5178.78	5031.03	4993.05
14	5780.82	5714.02	5648.98	5602.38	5538.08	5513.16	5447.55	5214.38	5175.45	5058.96	4921.39	4776.56
15	5741.59	5748.32	5576.39	5570.40	5536.83	5510.12	5505.58	5251.86	5223.97	5064.62	4974.42	4705.90
16	5653.20	5666.59	5572.22	5681.68	5496.24	5257.20	5518.04	5249.14	5137.45	5047.18	5112.71	4810.21
17	5596.21	5678.06	5587.27	5726.98	5538.60	5251.24	5504.79	5277.74	5127.87	5040.09	5045.95	4870.86
18	5749.96	5661.33	5597.39	5594.26	5570.33	5511.42	5315.10	5224.20	5148.10	5083.56	4952.51	4825.19
19	5761.62	5659.36	5607.86	5587.67	5578.64	5483.35	5316.82	5214.50	5146.36	5053.70	4912.83	4846.28
20	5762.75	5640.75	5612.15	5588.93	5572.84	5463.58	5322.43	5219.81	5151.43	5086.92	4908.83	4879.22
21	5760.99	5643.03	5598.81	5584.45	5548.49	5526.75	5331.85	5225.88	5123.50	5088.57	5007.81	4874.82
22	5757.84	5623.44	5618.56	5592.03	5564.35	5517.33	5340.18	5258.78	5123.41	5094.42	5008.49	4854.95
23	5756.99	5658.32	5471.53	5615.09	5568.80	5300.63	5313.12	5407.13	5224.76	4836.72	5110.14	5070.83
24	5755.00	5646.97	5656.31	5579.32	5580.27	5514.81	5355.83	5248.01	5180.02	5038.64	5044.73	5025.60
25	5752.16	5636.74	5615.22	5604.79	5580.81	5454.47	5355.09	5248.45	5182.76	5133.09	5090.02	5057.14
26	5642.58	5559.92	5603.67	5655.29	5430.69	5849.18	5083.83	5130.83	5348.32	5015.93	5194.97	5307.75
27	5739.45	5694.07	5644.69	5608.19	5588.16	5545.65	5417.36	5262.93	5247.75	5193.38	5098.23	4960.79
28	5750.96	5711.69	5667.19	5647.90	5596.65	5541.37	5343.44	5253.41	5207.93	5180.00	5107.59	4981.68
29	5675.92	5668.84	5683.11	5649.04	5689.27	5520.08	5366.64	5347.03	5148.16	5183.69	5115.24	4968.38
30	5713.57	5731.31	5672.48	5630.58	5549.23	5559.96	5292.56	5394.18	5239.55	5150.16	5108.48	4959.56
31	5725.98	5685.56	5658.42	5653.45	5636.23	5559.58	5364.04	5257.14	5223.36	5129.87	5108.37	5003.17
32	5746.38	5727.20	5656.70	5639.88	5629.48	5571.62	5373.18	5270.57	5238.99	5131.48	5109.66	5008.94
33	5800.65	5744.73	5648.44	5623.79	5596.80	5501.72	5363.48	5259.72	5216.25	5130.54	5105.48	4996.01
34	5841.92	5730.97	5666.62	5614.01	5600.88	5490.56	5350.34	5249.31	5206.13	5139.45	5119.01	5018.44
35	5604.41	5613.38	5837.42	5633.18	5600.85	5610.74	5699.05	5220.62	5335.72	5322.15	5024.18	5037.65
36	5850.71	5751.82	5636.20	5610.70	5586.02	5430.73	5373.08	5250.41	5200.34	5140.47	5107.35	4940.94
37	5862.98	5774.89	5640.63	5599.99	5640.00	5419.09	5355.89	5283.11	5198.44	5140.59	5107.79	4936.76
38	5860.64	5797.84	5671.57	5650.96	5615.59	5415.07	5358.10	5288.83	5210.74	5155.86	5101.09	4910.97
39	5849.50	5803.01	5686.50	5673.33	5598.50	5517.44	5350.09	5322.68	5202.12	5162.79	5107.24	4979.22
40	5847.88	5797.85	5731.30	5676.77	5621.36	5564.09	5347.33	5277.87	5198.22	5163.65	5110.20	4991.90
41	5686.33	5610.02	5742.96	5702.44	5766.89	5826.50	5234.14	5286.69	5342.30	5227.50	5111.21	4990.53
42	5845.25	5798.46	5742.61	5690.37	5652.22	5573.64	5354.16	5230.38	5209.42	5175.17	5116.75	4991.26
43	5792.62	5764.65	5715.98	5695.32	5664.85	5568.74	5394.20	5227.06	5200.88	5166.74	5125.09	4970.39
44	5792.84	5766.07	5720.72	5674.86	5689.65	5614.80	5405.32	5225.16	5203.06	5159.10	5110.96	4987.87
45	5767.61	5726.82	5705.84	5816.50	5665.87	5662.87	5443.60	5225.65	5171.21	5160.34	5120.16	5046.60
46	5783.47	5765.74	5731.67	5828.03	5678.99	5638.90	5391.71	5210.75	5165.06	5157.44	5107.90	5051.82
47	5844.14	5824.69	5781.52	5696.94	5675.91	5558.54	5409.03	5193.73	5174.80	5139.48	5056.83	5038.15
48	5861.47	5822.70	5789.74	5709.07	5683.23	5562.15	5387.80	5200.57	5170.13	5143.65	5080.05	4996.50
49	5842.88	5816.59	5785.46	5699.93	5600.86	5502.61	5248.68	5209.64	5162.66	5127.20	5101.85	4959.02
50	5856.26	5803.57	5777.37	5693.21	5603.27	5503.43	5383.50	5218.49	5149.76	5122.52	5088.20	4907.58
51	5855.29	5802.00	5769.80	5692.13	5597.38	5496.99	5447.54	5224.91	5152.09	5105.10	5048.55	4960.30
52	5845.77	5805.55	5752.76	5691.56	5613.27	5503.80	5434.72	5218.34	5141.85	5104.91	5042.29	4916.42

Appendix A4: Groundwater storage-reliability data at 30% GRSL

	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY											
WEEK	5	10	20	25	30	40	50	60	70	80	90	98
1	7779.83	7755.01	7645.69	7532.67	7386.82	7329.14	7210.79	6978.28	6876.09	6801.79	6733.75	6550.49
2	7804.80	7662.44	7635.28	7533.08	7387.28	7302.95	7170.94	6982.18	6906.31	6835.54	6745.31	6448.48
3	7822.39	7676.30	7625.61	7524.33	7390.56	7289.79	7180.28	6984.06	6884.67	6853.07	6757.40	6465.54
4	7642.70	7639.94	7612.79	7507.52	7327.78	7317.43	7210.66	6969.05	6854.72	6895.92	6765.39	6464.45
5	7813.53	7622.94	7552.25	7528.47	7506.55	7388.30	7290.52	6948.20	6872.74	6793.06	6737.46	6380.81
6	7800.51	7601.61	7599.03	7423.23	7503.91	7412.12	7361.68	6929.03	6883.21	6786.21	6597.55	6349.82
7	7706.97	7562.59	7626.01	7513.44	7479.46	7343.48	7332.97	6935.73	6845.19	6789.50	6526.88	6329.45
8	7759.66	7663.43	7590.55	7521.43	7408.78	7346.55	7225.14	6969.11	6797.43	6742.03	6591.35	6327.11
9	7754.50	7645.18	7585.53	7493.81	7405.75	7366.41	7301.33	6973.75	6792.11	6748.81	6583.60	6318.79
10	7747.44	7636.26	7589.40	7454.00	7408.37	7340.11	7240.59	6968.62	6804.59	6705.58	6775.44	6648.65
11	7732.61	7585.04	7554.86	7425.59	7384.53	7279.93	7256.07	6948.00	6811.13	6712.26	6585.23	6480.91
12	7712.52	7566.75	7550.25	7450.11	7327.93	7266.44	7305.30	6983.72	6799.72	6539.88	6621.84	6613.07
13	7716.13	7563.01	7521.69	7457.08	7399.55	7359.73	7221.21	6923.03	6884.09	6708.04	6528.47	6395.68
14	7707.76	7618.69	7531.97	7469.83	7384.10	7350.88	7263.40	6952.50	6900.60	6745.29	6561.85	6368.75
15	7664.43	7576.44	7510.58	7435.19	7402.09	7358.31	7282.22	7002.48	6913.06	6752.82	6610.16	6274.53
16	7555.45	7484.36	7550.49	7429.62	7439.11	7314.88	7295.39	6998.86	6903.47	6729.57	6673.11	6413.61
17	7570.74	7635.98	7461.61	7468.36	7358.62	7429.67	7203.95	6920.54	6890.56	6727.93	6716.91	6494.48
18	7666.62	7548.44	7463.19	7459.01	7427.10	7348.56	7086.80	6965.59	6864.13	6778.09	6603.35	6433.59
19	7682.16	7545.82	7477.14	7429.75	7445.73	7350.40	7089.09	7067.68	6814.83	6720.71	6461.70	6469.71
20	7809.50	7540.55	7447.06	7482.87	7451.91	7420.33	7225.89	6808.17	6827.33	6794.36	6621.30	6545.10
21	7681.32	7520.55	7465.08	7445.93	7397.99	7369.00	7109.13	6967.84	6831.34	6784.75	6677.08	6499.76
22	7677.12	7549.00	7494.46	7424.31	7456.03	7356.44	7120.24	7011.71	6895.74	6802.03	6677.99	6473.27
23	7675.99	7544.43	7456.69	7491.87	7395.29	7422.06	7139.10	7084.16	6966.34	6815.42	6718.59	6448.96
24	7673.33	7529.29	7491.80	7447.98	7439.09	7353.08	7141.10	6997.34	6880.21	6822.39	6726.31	6700.80
25	7669.55	7515.65	7495.00	7486.96	7445.53	7272.63	7094.87	6997.94	6904.26	6759.08	6786.70	6742.85
26	7643.44	7540.22	7492.49	7473.65	7413.23	7335.61	7219.75	7004.82	6980.95	6914.10	6791.21	6687.90
27	7652.60	7592.09	7532.60	7477.59	7450.88	7394.19	7223.14	7017.24	6997.00	6924.51	6797.63	6614.39
28	7667.94	7615.58	7556.25	7530.54	7462.20	7388.49	7124.59	7004.55	6943.90	6906.67	6810.12	6642.24
29	7660.70	7585.69	7558.45	7536.49	7505.00	7384.21	7155.52	6989.73	6911.59	6864.22	6807.34	6624.50
30	7642.41	7618.10	7548.92	7527.58	7518.21	7398.98	7164.34	6986.07	6932.53	6843.91	6811.31	6612.75
31	7576.97	7634.64	7540.55	7492.56	7580.75	7412.78	7152.05	6989.97	7052.93	6826.05	6861.73	6670.89
32	7661.84	7636.26	7542.27	7519.84	7505.98	7428.83	7164.24	7027.42	6985.31	6841.97	6812.88	6678.59
33	7734.19	7659.64	7531.26	7498.39	7462.40	7335.62	7151.31	7012.96	6955.01	6840.72	6807.30	6661.34
34	7795.95	7641.29	7518.39	7474.05	7467.84	7320.75	7133.78	6999.08	6941.51	6852.60	6825.34	6691.25
35	7783.23	7625.50	7510.90	7484.50	7472.54	7265.83	7147.43	6984.65	6950.83	6858.53	6806.14	6698.91
36	7800.95	7636.88	7448.03	7480.93	7481.42	7333.89	7164.11	6976.26	6933.79	6853.96	6809.80	6587.92
37	7812.67	7699.85	7520.84	7518.57	7467.00	7225.45	7141.18	7041.76	6931.25	6864.07	6810.38	6582.35
38	7814.19	7564.44	7562.10	7634.52	7448.32	7180.12	7135.07	7051.77	6909.17	6547.96	6947.65	6670.17
39	7799.34	7569.03	7582.00	7654.51	7421.25	7356.59	7104.37	7111.20	6911.20	6688.19	6980.16	6638.96
40	7797.17	7730.46	7641.74	7558.00	7495.14	7418.79	7129.78	7037.17	6930.96	6884.87	6813.61	6655.87
41	7768.67	7715.82	7657.28	7603.26	7519.94	7480.03	7107.81	6968.19	6933.52	6891.36	6814.95	6654.04
42	7793.67	7706.80	7656.81	7494.98	7544.91	7482.37	7096.49	6946.16	6941.36	6889.03	6822.33	6655.01
43	7723.49	7686.21	7621.31	7593.76	7577.33	7424.98	7192.26	6969.42	6934.50	6888.99	6833.45	6627.19
44	7723.79	7688.10	7627.63	7566.48	7606.68	7486.40	7207.09	6966.88	6937.42	6878.80	6814.61	6650.49
45	7723.50	7641.91	7635.76	7755.33	7554.49	7584.87	7179.85	6922.13	6895.45	6880.45	6826.88	6728.80
46	7770.71	7711.29	7677.09	7606.63	7571.99	7432.09	7188.95	6947.67	6892.61	6846.52	6810.53	6735.76
47	7792.18	7766.25	7708.70	7595.91	7567.87	7411.39	7212.05	6924.97	6899.73	6852.63	6742.44	6717.53
48	7815.29	7763.60	7719.66	7612.10	7593.14	7416.20	7183.74	6934.09	6893.50	6858.21	6773.41	6662.01
49	7808.53	7755.46	7713.95	7599.91	7467.81	7336.82	7175.82	6946.18	6889.97	6836.26	6781.64	6612.02
50	7808.34	7800.75	7703.16	7471.03	7373.30	7269.26	7177.99	6957.98	6866.34	6830.03	6784.27	6543.44
51	7807.05	7736.00	7693.07	7589.50	7463.17	7329.32	7263.39	6966.54	6869.46	6806.80	6731.39	6613.73
52	7794.36	7740.73	7670.35	7588.75	7484.36	7338.40	7246.29	6895.59	6828.04	6753.63	6692.47	6555.23

Appendix A5: Groundwater storage-reliability data at 40% GRSL

WE	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY											
EK	5	10	20	25	30	40	50	60	70	80	90	98
1	11669.75	11632.51	11468.54	11299.01	11080.23	10993.71	10816.18	10467.42	10314.14	10202.69	10100.63	9825.73
2	11707.20	11556.05	11432.60	11347.93	11299.62	11075.45	10843.54	10473.27	10356.21	10205.07	10117.97	9672.72
3	11733.58	11514.35	10847.11	11338.97	11286.50	11060.34	10975.45	10476.09	10334.26	10211.99	10136.11	9698.31
4	11464.05	11424.84	10923.66	11331.44	11261.28	11052.23	11247.26	10453.58	10298.25	10204.85	10148.08	9696.68
5	11720.29	11434.41	11328.38	11292.70	11259.83	11082.45	10935.79	10422.30	10309.11	10189.59	10106.19	9571.21
6	11700.76	11419.07	11379.72	11277.84	11192.86	11118.18	10963.41	10412.55	10324.82	10179.32	9958.27	9524.73
7	11560.45	11143.61	11387.32	11283.89	11127.54	11015.22	10968.42	10476.65	10267.78	10184.24	9948.01	9494.17
8	11639.50	11463.16	11441.42	11295.07	11239.82	11019.82	10964.11	10213.35	10196.14	10113.04	9833.79	9490.67
9	11631.75	11467.77	11378.30	11240.72	11108.63	11049.61	10951.99	10460.63	10188.16	10123.22	9875.39	9478.18
10	11621.16	11431.06	11377.99	11181.00	11112.56	10992.70	10860.89	10452.93	10206.88	10137.70	9972.97	9892.95
11	11598.92	11377.57	11332.29	11138.38	11094.44	10919.89	10830.65	10421.99	10225.28	10146.63	9886.77	9721.36
12	11568.77	11356.21	11325.37	11170.43	11088.07	10957.95	10884.44	10407.13	10269.50	9975.55	9910.31	9809.81
13	11574.20	11351.32	11282.53	11193.44	11099.32	10875.10	10777.78	10528.52	10357.55	10202.25	9853.44	9986.11
14	11561.64	11428.03	11297.96	11204.75	11026.32	10895.10	10705.05	10574.51	10428.75	10117.93	10006.27	9858.97.
15	11496.65	11364.66	11265.87	11152.79	11103.14	11037.47	10923.33	10503.73	10369.58	10129.24	9915.24	9411.80
16	11363.36	11389.37	11325.74	11306.39	11158.67	11218.71	10972.33	10355.21	10390.31	10274.91	10073.64	9620.42
17	11453.96	11424.01	11121.35	11192.42	11144.50	11218.44	10921.72	10321.87	10380.81	10255.73	10075.37	9741.72
18	11499.92	11322.66	11194.78	11188.52	11140.65	11022.84	10630.20	10448.39	10296.20	10167.13	9905.03	9650.38
19	11397.44	11318.72	11168.59	11215.72	11224.98	11157.27	10633.64	10222.22	10333.44	10292.72	9825.66	9704.57
20	11336.93	11281.49	11151.56	11224.31	11310.83	11145.68	10644.85	10187.21	10241.00	10302.86	9817.65	9931.95
21	11521.98	11280.83	11197.61	11168.90	11096.98	11053.50	10663.70	10451.76	10247.00	10177.13	10015.62	9749.64
22	11515.68	11246.87	11195.25	11176.26	11128.71	11034.66	10680.37	10517.57	10246.83	10188.84	10016.98	9709.90
23	11513.98	11247.88	11230.18	11160.54	11137.59	11133.09	10708.64	10626.24	10141.66	10261.13	10077.89	9673.45
24	11509.99	11293.94	11237.69	11171.97	11158.64	11029.62	10711.65	10496.01	10320.31	10233.58	10089.47	10051.21
25	11504.32	11297.24	11242.51	11222.03	11112.66	10794.96	10710.18	10479.09	10193.56	10266.19	10138.61	10114.28
26	11465.16	11310.58	11243.10	11207.33	11119.85	10829.63	10861.38	10474.87	10186.81	10261.66	10167.66	10389.93
27	11478.90	11388.13	11298.89	11216.39	11176.32	11091.29	10834.72	10525.86	10495.50	10386.76	10196.45	9921.58
28	11501.91	11082.73	11215.61	11346.69	11308.54	11369.59	10877.15	9963.36	10541.89	10423.28	10233.29	10367.64
29	11351.84	11040.16	11257.51	11335.79	11304.73	11430.35	10857.96	9936.75	10349.47	10484.59	10211.02	10324.13
30	11463.62	11427.14	11323.38	11291.37	11277.31	11098.46	10746.51	10479.10	10398.79	10265.86	10216.96	9919.13
31	11430.13	11365.46	11330.27	11310.83	11451.96	11139.73	10514.29	10579.39	10446.73	10295.67	10239.07	10006.33
32	11454.39	11243.65	11330.76	11279.76	11492.76	11289.11	10477.97	10661.01	10485.65	10322.00	10240.33	10017.88
33	11601.29	11489.45	11296.89	11247.58	11193.60	11003.44	10726.96	10519.43	10432.51	10261.08	10210.96	9992.02
34	11693.92	11461.94	11277.59	11211.08	11201.77	10981.12	10700.67	10498.62	10412.26	10278.89	10238.01	10036.88
35	11438.24	11601.82	11345.13	10914.06	11201.70	11265.68	10744.10	10441.24	10476.98	10266.36	10075.30	10048.36
36	11701.43	11503.64	11272.40	11221.40	11172.04	10861.46	10746.16	10500.82	10400.68	10280.94	10214.71	9881.88
37	11725.96	11549.77	11281.27	11199.98	11280.01	10838.17	10711.77	10566.22	10396.88	10281.19	10215.57	9873.53
38	11721.29	11554.78	11343.15	11301.92	11346.66	10770.19	10716.20	10423.79	10421.47	10311.71	10202.19	9821.94
39	11699.01	11606.02	11373.00	11353.55	11197.00	11034.89	10700.18	10645.35	10404.24	10325.57	10214.49	9958.43
40	11695.76	11595..69	11462.60	11336.99	11242.71	11128.19	10694.66	10555.75	10396.44	10327.30	10220.41	9983.80
41	11653.00	11573.74	11476.06	11372.65	11304.45	11155.35	10688.66	10468.28	10404.22	10351.84	10222.42	9981.06
42	11690.51	11560.20	11380.73	11329.70	11605.19	10957.97	10614.90	10644.74	10419.24	10354.22	10233.49	10091.89
43	11585.23	11529.31	11431.96	11390.63	11366.00	11137.47	10788.40	10454.13	10401.75	10333.49	10250.17	9940.78
44	11605.94	11532.15	11410.02	11391.86	11305.02	11145.93	10810.63	10416.77	10358.27	10299.21	10221.91	9975.73
45	11633.00	11535.21	11431.40	11377.30	11331.73	11133.66	10887.20	10451.31	10343.18	10290.55	10240.32	10093.20
46	11656.07	11566.94	11515.63	11409.94	11357.98	11148.14	10783.42	10421.51	10338.91	10269.78	10215.79	10103.64
47	11688.27	11649.37	11563.04	11393.87	11351.81	11117.09	10818.07	10387.45	10349.60	10278.95	10113.66	10076.29
48	11722.94	11645.39	11579.49	11418.15	11389.71	11124.29	10775.60	10401.14	10340.25	10287.31	10160.11	9993.01
49	11712.80	11685.75	11570.93	10885.25	11399.86	11189.12	10763.73	10419.27	10334.96	10254.40	10172.46	9918.03
50	11701.13	11712.51	11554.75	10903.89	11386.42	11059.94	10740.72	10436.97	10328.11	10245.05	10229.78	9815.15
51	11710.58	11604.00	11539.61	11384.25	11194.76	10993.99	10895.09	10449.81	10304.18	10210.19	10097.09	9920.60
52	11691.55	11611.10	11505.52	11383.12	11226.53	11007.59	10869.43	10343.39	10242.06	10130.44	10038.71	9832.85

Appendix A6: Groundwater storage-reliability data at 60% GRSL

WE	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY											
EK	5	10	20	25	30	40	50	60	70	80	90	98
1	15559.67	15510.01	15291.39	15065.34	14773.64	14658.28	14421.58	13956.56	13752.19	13603.59	13467.51	13100.98
2	15609.60	15324.88	15270.56	15066.16	14774.56	14605.90	14341.88	13964.35	13812.62	13671.09	13490.63	12896.96
3	15644.77	15352.60	15251.22	15048.66	14781.13	14579.58	14360.57	13968.12	13769.34	13706.13	13514.81	12931.08
4	15628.44	15279.89	15223.50	15015.04	14785.17	14709.19	14564.88	13883.20	13709.43	13593.42	13530.78	12928.91
5	15627.06	15056.94	15332.98	15013.11	15034.01	14642.27	14581.05	13884.29	13745.48	13574.74	13474.92	12761.62
6	15601.02	14846.46	15362.96	15007.82	14923.82	14894.91	14723.36	13928.79	13766.42	13542.44	13195.10	12699.64
7	15413.93	15252.02	15159.17	15045.18	14958.91	14716.58	14624.56	13871.47	13661.75	13560.79	13264.01	12658.89
8	15519.33	15255.23	15284.21	14986.43	14450.28	14703.26	14660.90	13820.37	13617.80	13326.19	13182.70	12654.22
9	15509.00	15226.20	15291.53	14903.49	14734.50	14653.65	14655.93	13792.09	13571.13	13040.31	13224.33	12637.57
10	15494.88	15241.41	15170.66	14908.00	14816.75	14656.93	14481.18	13937.24	13609.17	13516.93	13297.29	13190.60
11	15465.23	15170.09	15109.73	14851.17	14792.59	14559.86	14440.87	13895.99	13633.71	13528.85	13182.36	12961.82
12	15425.03	15133.50	15100.50	14900.21	14784.10	14532.88	14356.20	13967.44	13736.10	13621.14	13093.33	13226.13
13	13846.07	14370.37	13768.18	12961.65	12791.37	13764.39	14799.54	14725.10	14924.59	15043.37	15050.79	14799.10
14	15415.52	15237.38	15063.94	14939.67	14768.21	14701.76	14526.81	13905.01	13801.20	13490.57	13123.70	12737.49
15	15310.90	15328.87	14870.38	14854.39	14764.89	14693.65	14681.54	14004.97	13930.58	13505.65	13265.12	12549.07
16	15075.19	15110.90	14859.25	15151.15	14656.63	14019.20	14714.78	13997.71	13699.87	13459.14	13633.89	12827.22
17	15232.02	15141.49	14936.72	14899.40	14828.47	14679.44	14288.12	13841.07	13762.50	13455.86	13400.56	12988.96
18	15235.06	15096.87	14918.03	14926.38	14786.56	14698.05	14173.61	13832.39	13728.26	13565.71	13206.70	13024.60
19	15196.59	15091.63	14859.50	14954.29	14876.36	14622.25	14178.18	13777.92	13629.66	13629.62	12923.41	13100.88
20	15367.33	15081.11	14965.74	14894.13	14860.90	14750.28	14451.78	13919.51	13654.67	13582.94	13242.60	13011.27
21	15362.65	15041.11	14930.15	14891.86	14795.97	14738.00	14218.26	13935.68	13662.67	13569.51	13354.15	12999.52
22	15354.24	15097.99	14988.92	14848.61	14912.07	14712.88	14240.49	14023.42	13791.47	13604.07	13355.98	12946.54
23	15351.97	14997.18	14972.85	14880.72	14844.11	14790.58	14278.19	14007.54	13681.51	13634.34	13522.22	12897.93
24	15346.66	15058.59	14983.59	14895.96	14878.18	14706.16	14282.20	13994.69	13760.42	13644.78	13452.63	13401.61
25	15339.10	15031.30	14990.01	14973.93	14891.06	14545.25	14189.74	13995.87	13808.51	13518.15	13573.39	13485.71
26	15286.87	15080.44	14984.99	14947.31	14826.46	14671.22	14439.50	14009.63	13961.91	13828.21	13582.41	13375.81
27	15305.21	15052.50	15065.19	14788.39	14818.67	15245.24	14446.29	13994.00	14000.84	14005.71	13595.27	13228.77
28	15322.88	15159.45	15078.05	14924.41	14776.97	15231.17	14550.78	13897.71	14059.14	13916.36	13620.23	13284.48
29	15321.39	15171.38	15116.90	15072.98	15010.01	14768.41	14311.03	13979.45	13823.17	13728.43	13614.69	13249.01
30	15284.83	15283.48	15126.62	15075.87	15048.09	14792.21	14303.29	14013.67	13872.57	13865.05	13622.62	13225.50
31	15153.94	15240.17	15089.12	15092.09	15063.55	14852.98	14328.08	14019.05	13928.97	14105.86	13723.45	13341.78
32	15323.68	15272.52	15084.54	15039.68	15011.96	14857.66	14328.49	14054.85	13970.63	13683.95	13625.76	13357.18
33	15387.42	15319.27	15140.77	15014.40	14989.85	14881.98	14302.62	14025.91	13910.01	13690.80	13567.28	13322.69
34	15438.37	15282.58	15169.28	15110.99	14970.69	14897.73	14267.56	13998.16	13883.01	13658.06	13608.39	13382.50
35	15566.46	15250.99	15021.80	14969.01	14945.08	14531.65	14294.86	13969.30	13901.66	13717.07	13612.28	13397.82
36	15601.90	15273.76	14896.06	14961.87	14962.84	14667.77	14328.22	13952.52	13867.57	13707.92	13619.61	13175.84
37	15634.61	15396.08	15040.01	14933.31	14982.07	15037.15	14282.36	13915.02	13862.51	13708.25	13620.77	13164.70
38	15628.39	15460.91	15128.88	15069.23	14974.91	14440.19	14288.27	14103.54	13895.29	13748.95	13602.91	13095.92
39	15598.68	15474.70	15138.06	14929.34	14973.77	14402.78	14266.91	14222.39	13960.32	13767.43	13619.32	13376.39
40	13786.50	13824.75	13846.28	13716.36	14250.04	14074.33	14159.06	15283.47	15169.47	14872.35	14837.58	15491.93
41	15537.34	15431.65	15301.41	15163.54	15072.60	14873.80	14251.55	13957.71	13872.30	13802.46	13629.89	13308.08
42	15587.34	15413.61	15243.05	15174.31	15106.26	14863.04	14153.19	13947.67	13891.78	13805.62	13644.66	13310.03
43	15187.51	15432.53	15242.61	15190.01	15172.40	14858.64	13975.67	13938.84	13890.47	13777.99	13666.89	13254.37
44	15474.59	15376.19	15213.36	15189.14	15073.37	14861.24	14414.18	13889.03	13811.03	13732.29	13629.21	13300.98
45	15510.66	15380.29	15241.86	15169.74	15108.98	14844.87	14516.27	13935.08	13790.91	13720.74	13653.76	13457.60
46	15541.43	15403.21	15213.25	15143.97	15037.08	14864.19	14270.47	13895.34	13856.46	13753.19	13693.04	13471.52
47	15584.36	15532.50	15417.39	15191.83	15135.75	14822.79	14424.09	13849.94	13799.46	13705.27	13484.89	13435.06
48	15630.58	15527.19	15439.32	15224.19	15186.27	14832.39	14367.47	13868.19	13787.00	13716.41	13546.81	13324.01
49	15617.07	15581.00	15427.90	14513.66	15199.81	14918.83	14351.63	13892.36	13779.95	13672.53	13563.28	13224.04
50	15616.68	15476.18	15406.33	15181.89	14942.05	14675.83	14355.99	13915.96	13732.69	13660.06	13568.55	13086.87
51	14570.81	15404.52	14526.78	15416.29	14718.85	15614.10	14658.65	13804.98	13300.54	13717.30	13927.15	13628.10
52	15588.73	15481.46	15340.69	15177.50	14968.71	14676.79	14492.57	13791.19	13656.08	13507.25	13384.95	13110.46

Appendix A7: Groundwater storage-reliability data at 80% GRSL

WEEK	GROUNDWATER STORAGES AT DIFFERENT LEVELS OF RELIABILITY											
	5	10	20	25	30	40	50	60	70	80	90	98
1	19449.59	19387.52	19114.24	18831.68	18467.05	18322.85	18026.97	17445.71	17190.23	17004.48	16834.38	16376.22
2	19512.00	19260.08	19054.33	18913.22	18832.70	18459.08	18072.56	17455.44	17260.35	17008.44	16863.28	16121.19
3	19555.97	19190.58	18078.52	18898.29	18810.83	18433.91	18292.42	17460.15	17223.77	17019.98	16893.51	16163.85
4	19106.75	19041.41	18206.10	18885.73	18768.81	18420.39	18745.43	17422.63	17163.76	17008.08	16913.47	16161.14
5	19533.82	19057.35	18880.63	18821.17	18766.38	18470.75	18226.31	17370.50	17181.85	16982.65	16843.65	15952.02
6	19501.27	19004.03	18997.57	18558.07	18759.78	18530.29	18404.20	17322.56	17208.03	16965.53	16493.87	15874.55
7	19267.41	18906.47	19065.03	18783.60	18698.64	18358.69	18332.43	17339.33	17112.96	16973.74	16317.20	15823.61
8	19399.16	19158.57	18976.36	18803.58	18521.96	18366.37	18062.85	17422.78	16993.57	16855.07	16478.38	15817.78
9	19386.25	19112.95	18963.83	18734.53	18506.62	18416.02	18418.13	17434.38	17009.57	16860.73	16530.41	15796.96
10	19368.60	19090.64	18973.49	18635.00	18321.16	18350.26	18317.80	17421.55	17031.53	16792.45	16512.88	16621.62
11	19331.54	18962.61	18887.16	18563.97	18490.74	18199.82	18051.09	17369.99	17042.13	16911.06	16477.95	16202.27
12	19281.29	18916.88	18875.62	18625.26	18480.12	18166.10	17945.26	17459.30	17170.13	17026.43	16366.66	16532.67
13	19290.34	18904.26	18804.22	18655.73	18499.43	18406.38	17962.97	17547.53	17262.59	17003.76	16202.06	16643.51
14	19269.41	19046.72	18829.93	18674.59	18460.26	18377.20	18158.51	17381.26	17251.50	16863.21	16404.62	15921.87
15	19138.63	19161.08	18587.98	18567.99	18456.11	18367.06	18351.92	17506.21	17413.22	16882.06	16581.40	15686.33
16	18843.98	18888.63	18574.06	18938.94	18320.79	17524.00	18393.48	17497.14	17124.84	16823.92	17042.36	16034.03
17	19040.02	18926.86	18670.91	18624.25	18535.58	18349.30	17860.15	17301.34	17203.12	16819.82	16750.70	16236.20
18	19043.83	18871.09	18647.54	18657.97	18483.20	18372.57	17717.01	17290.48	17160.33	16957.14	16508.38	16280.75
19	18995.73	18864.54	18574.38	18692.86	18595.45	18277.82	17722.73	17222.40	17037.08	17037.03	16154.26	16376.10
20	19209.16	18851.39	18707.18	18617.66	18576.13	18437.86	18064.73	17399.38	17068.33	16978.68	16553.26	16264.08
21	19203.31	18728.54	18736.64	18614.83	18419.69	18479.29	18422.50	17464.57	17048.35	17021.47	16774.55	16620.07
22	19192.80	18627.10	18733.88	18560.77	18478.17	18476.92	18391.10	17534.91	17039.53	16664.81	16898.73	16981.40
23	19189.97	18746.47	18716.06	18600.89	18555.14	18488.23	17847.74	17509.43	17101.89	17042.93	16902.77	16122.41
24	19183.32	18823.23	18729.49	18619.95	18597.73	18382.70	17852.75	17493.36	17200.52	17055.97	16815.78	16752.01
25	19173.87	18789.13	18737.51	18717.41	18613.82	18181.57	17737.17	17494.84	17260.64	16897.69	16966.74	16857.14
26	19108.59	18850.55	18731.23	18684.14	18533.08	18339.02	18049.38	17512.04	17452.38	17285.26	16978.01	16719.76
27	19131.51	18980.22	18831.49	18693.98	18627.20	18485.49	18057.86	17543.10	17492.50	17311.27	16994.09	16535.97
28	19153.60	19169.85	18847.56	18573.63	18614.25	18655.51	18188.47	17359.75	17372.13	17279.40	17025.29	16605.60
29	19151.74	18919.74	18841.22	18564.47	18732.22	18964.22	18460.52	17160.54	17474.32	17206.88	17050.79	16561.26
30	19106.04	19045.24	18872.29	18818.95	18795.52	18497.44	17910.86	17465.16	17331.31	17109.77	17028.27	16531.88
31	18942.43	19086.60	18851.38	18731.41	18951.88	18531.95	17880.13	17474.93	17632.32	17065.12	17154.32	16677.22
32	18739.42	19154.60	18799.59	18658.99	19139.76	18572.08	17923.66	17568.56	17768.35	17067.22	17053.79	16696.47
33	18612.80	19234.27	18768.01	18656.00	19335.48	18602.48	17933.44	17532.39	17719.54	17101.80	17097.96	16653.36
34	19473.06	19103.23	18888.74	18713.36	18669.61	18301.87	17834.45	17497.70	17353.76	17131.49	17063.35	16728.13
35	19458.08	19063.74	18777.26	18711.26	18681.35	18164.57	17797.66	17461.63	17302.76	17146.33	17123.11	16792.17
36	19502.38	19092.21	18620.07	18702.33	18703.54	18334.72	17789.94	17440.65	17265.92	17134.90	17185.81	16738.04
37	19531.68	19249.62	18802.11	18796.43	18667.49	18063.62	17852.95	17604.40	17328.13	17160.17	17025.96	16455.88
38	19567.71	19257.97	18814.42	19086.29	18836.54	17950.31	17860.34	17629.42	17286.99	17186.18	17003.64	16369.90
39	19588.62	19247.26	18947.20	19136.26	18661.67	18391.48	17833.64	17777.99	17318.24	17209.29	17024.15	16720.48
40	19492.93	19326.16	19104.34	18894.99	18737.85	18546.98	17824.44	17592.92	17327.39	17212.16	17034.02	16639.67
41	19421.67	19289.56	19143.20	19008.14	18799.86	18700.08	17769.53	17420.46	17333.80	17228.39	17037.37	16635.10
42	19484.18	19267.01	19142.03	18737.44	18862.28	18705.92	17741.23	17365.40	17353.40	17222.58	17055.82	16637.54
43	19308.72	19215.51	19053.26	18984.39	18943.33	18562.45	17980.66	17423.55	17336.25	17222.48	17083.62	16567.97
44	19309.47	19220.24	19069.07	18916.20	19016.71	18716.00	18017.72	17417.19	17343.54	17196.99	17036.52	16626.22
45	19308.74	19225.36	19052.33	18886.22	19104.77	19019.46	17989.75	17418.85	17305.32	17238.64	17059.66	16821.99
46	19426.78	19278.23	19192.72	19016.56	18929.97	18580.24	17972.37	17369.18	17231.52	17116.31	17026.32	16839.40
47	19415.62	19437.91	19480.45	18989.79	18919.69	18649.44	17950.72	17297.97	17249.33	17062.17	16856.11	16808.90
48	19403.54	19449.81	19685.01	18982.84	19030.24	18656.79	17948.34	17263.84	17309.26	17070.54	16655.01	16858.91
49	19521.34	19388.64	19284.88	18999.77	18669.52	18342.04	17939.54	17365.45	17224.93	17090.66	16954.10	16530.05
50	19501.88	19345.22	19257.91	18977.37	18677.57	18344.78	17901.21	17394.95	17213.52	17075.08	17049.64	16358.59
51	19486.84	19340.00	19232.68	18973.75	18624.29	18398.56	17786.05	17416.35	17256.22	17053.61	17035.13	16534.33
52	19485.91	19351.83	19175.87	18971.87	18710.89	18345.99	18115.72	17238.98	17070.09	16884.06	16731.18	16388.08

Appendix A8: Groundwater storage-reliability data of 100% GRSL