

**APPLICATION OF THE MODIFIED PITMAN AND SWAT MODELS
FOR GROUNDWATER RECHARGE ESTIMATION IN THE
UPSTREAM AREA OF THE UITENHAGE ARTESIAN BASIN, SOUTH
AFRICA**

**Dissertation submitted to Rhodes University in fulfilment of the
requirements for the Master of Science Degree in Hydrology**

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FEBRAURY 2024

DECLARATION

The wholeness of the current dissertation has never been submitted for academic purposes in any institution and therefore, I declare that it is my original work, and, in any case, materials written by other authors have been acknowledged.

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.....06-02-2024.....

Date

Keywords: MODIFIED PITMAN, SWAT, GROUNDWATER RECHARGE, UAB, SOUTH AFRICA

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DEDICATION

To my dear late parents, David Sserunkuuma and Kamiat Nabatelega who were not able to see this fruition.

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LIST OF ACRONYMS

95PPU	95 Percent Prediction Uncertainty
AET	Actual Evapotranspiration
AGEP	Average Groundwater Exploitation Potential
AHP	Analytic Hierarchy Process
ANN	Artificial Neural Networks
ARC	Agricultural Research Council
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
CFSR	Climate Forecast System Reanalysis
CGIAR-CSI	CGIAR Consortium for Spatial Information
CMB	Chloride Mass Balance
CRD	Cumulative Rainfall Departure
CTI	Compound Topographic Index
CWB	Channel Water Budget
DBM	Data-Based Mechanistic models
DEM	Digital Elevation Model
DWS	Department of Water and Sanitation
EARTH	Extended Model for Aquifer Recharge and moisture Transport through unsaturated Hardrock
EVSF	Equal Volume Spring Flow
EWR	Environmental Water Requirements
FDC	Flow Duration Curve
GLUE	Generalised Likelihood Uncertainty Estimation
GM	Groundwater Modelling
GRAII	Groundwater Resource Assessment Phase II
GWPI	Groundwater Potential Index
HAND	Height Above the Nearest Drainage
HRU	Hydrological Response Unit
HWSD	Harmonized World Soil Database
IDW	Inverse Distance Weighting
ITCZ	Inter-Tropical Convergence Zone
IWRM	Integrated Water Resource Management
KGE	Kling-Gupta efficiency
MAP	Mean Annual Precipitation
MCMC	Markov Chain Monte Carlo
MK	Mann-Kendall
NASA	National Aeronautics and Space Administration
NSE	Nash Coefficient of Efficiency
PARASOL	Parameter Solution
PBIAS	Percent Bias
PC	Plan Curvature
PET	Potential Evapotranspiration
PDEs	Partial Differential Equations
QGIS	Quantum Geographical Information System
RIB	Rainfall Infiltration Breakthrough
SADC	Southern African Development Community
SANLC	South African National Land-Cover
SAWS	South Africa Weather Services
SOTER	Soil and Terrain

SOTERSAF	Soil and Terrain Database for Southern Africa
SPATSIM	SPatial and Time Series Information Modelling
SRTM	Shuttle Radar Topography Mission
SUFI-2	Sequential Uncertainty Fitting algorithm-2
SVF	Saturated Volume Fluctuation
SWAT	Soil Water Assessment Tool
SWAT-CUP	Calibration Uncertainty Program
TMG	Table Mountain Group
TMGS	Table Mountain Group Sandstones
TWI	Topographic Wetness Index
UAB	Uitenhage Artesian Basin
UFM	Unsaturated Flow Modelling
USDA-ARS	United States Department of Agriculture–Agricultural Research Services
UTM	Universe Transverse Mercator
WaPOR	Water Productivity through Open access of Remotely sensed derived data
WM	Watershed Modelling
WMA	Water Management Area
WTF	Water Table Fluctuation
WRC	Water Research Commission
WR2012	Water Resources Simulation Model 2012
WYLD	Water Yield
ZFP	Zero Flux Plane

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ABSTRACT

The world's most plentiful source of freshwater is thought to be groundwater. During extended dry times, it serves as an essential storage component and guards against environmental catastrophes. Despite its critical functions in the aforementioned scenarios, it is often insufficiently understood and inadequately managed. As a result, it calls for the adoption of integrated methods to comprehend the dynamics of groundwater recharge. Thus, the current study evaluated the applicability and suitability of the Modified Pitman and SWAT models for groundwater recharge estimation in the upstream area of UAB for the period that spanned from 1993 to 2021. It was achieved by using a qualitative conceptual-perceptual model to inform the two hydrological models, Modified Pitman, and SWAT.

The developed qualitative conceptual-perceptual model depicted the dominancy of irregularly folded and fractured TMG rock outcrops coupled with fault systems in the upstream area. In the downward section, TMG is overlaid by the aquiclude from the Uitenhage Group which is responsible for the artesian conditions. Groundwater potential zones were classified as Poor, Fair, Good, and Excellent, with 65.4% and 8.7% of the upstream area attributed to Good and Excellent zones respectively. Both Modified Pitman and SWAT predicted decreasing rates of groundwater recharge in the upstream area over time, though Mann-Kendal trend tests done at 5% significance level depicted significant decreasing rates in SWAT predicted recharge compared to Modified Pitman predicted recharge. The two models did also predict recharge and other water balance components with differing peaks, lows and timings. Modified Pitman predicted mean annual recharge of 63.3-92.8 mm where as SWAT predicted mean annual recharge of 14.4-182.8 mm.

In reference to earlier findings within TMG areas, estimated percentages of groundwater recharge were close to those simulated by both Pitman and SWAT models. Modified Pitman and SWAT models appear to both be reasonable tools to estimate recharge in TMG setting, producing relatively similar results to one another and to other regional estimates. Since the current study estimated low recharge rates (Modified Pitman; ~9.3-13.6% MAP), (SWAT; ~2.1-26.7% MAP) which are close to those predicted in other TMG areas, the study recommends exercising caution when developing a water supply strategy in the current study area. The recharge rates within the pertinent recharging areas should be considered when designing and siting abstraction points such as boreholes and a sustainable abstraction rate in any one borehole for improved sustainable management of groundwater resources.

CHAPTER ONE

INTRODUCTION

1.1 Background

The most plentiful source of freshwater in the world is thought to be groundwater. Globally, it provides roughly a quarter of agricultural water needs, over 50% of the water used for drinking, and about a third required for industrial uses (Doll et al., 2012). Most people in Africa rely on groundwater resources for their daily activities (MacDonald et al., 2009). Groundwater supply and use in some parts of Africa have been gaining increasing attention in the scientific world, with literature predicting a great increase in its exploitation in years to come (Nolte et al., 2021; Walker et al., 2019). Studies by (Hughes, 2019, 2004; Izady et al., 2012; Tanner, 2013) have highlighted that proper utilization of groundwater in dry areas of Africa will act as a key bearing point for the sustainable growth of societies.

When tested and declared potable, groundwater can be used to augment surface water resources during dry spells to meet water demands (Castle et al., 2014; Izady et al., 2014; Ndambuki et al., 2017; Ndhlovu and Woyessa, 2021; Nolte et al., 2021; Nyagwambo, 2006; Taylor et al., 2013). This and many others account for the reason why it is being abstracted beyond its natural recharge capacity. As such, understanding the dynamics of groundwater components, particularly groundwater recharge, is key given the dependence of communities on groundwater resources to satisfy their water needs.

Groundwater recharge is a critical variable in groundwater dynamics, though often difficult to measure accurately (Lorentz et al., 2003). Groundwater recharge is often used to define sustainable abstraction volumes as recharge replenishes the groundwater stock and represents a safe volume with no aquifer depletion occurring (Boerner and Weaver, 2012; Nyagwambo, 2006). Mqondeki (2019) defined groundwater recharge as water that flows vertically from precipitation until it reaches the water table via multiple processes. Groundwater recharge is a central indicator and an important variable in sustaining renewable freshwater resources in many dry regions of the world for humans and ecosystems (Herbert and Döll, 2019). Hence, understanding groundwater recharge dynamics is important for groundwater resource sustainable management (Green et al., 2011).

South Africa is a dry region with notable water scarcity issues which force the country to heavily depend on water obtained from groundwater sources for various needs (Gyamfi et al.,

2017; Hughes, 2019b; Xu et al., 2018). Much of South Africa has low and highly variable rainfall which reduces the volume of water in surface water resources thus leading to dependency on groundwater water resources (Ndambuki et al., 2017). In addition, there are areas that primarily rely on groundwater and most of the surface water resources are over allocated, leading to people to look to groundwater to allow further development.

Despite various advances in hydrology, obtaining accurate estimates of groundwater recharge remains difficult, particularly in dry regions (Baron, 2000; Izady et al., 2015; Maclear, 2001; Ndambuki et al., 2017; Nolte et al., 2021; Sami and Hughes, 1996; Xu et al., 2018). It is because groundwater recharge fluxes in comparison with average areal rainfall are generally low (Lerner, 1990; Martinez et al., 2015; Watson et al., 2020). In the same line, Rukundo and Doğan (2019) stated that, the requirement of various input data, for example, land use, soils, topography and hydrological data with various spatial and temporal ranges, complicates the interpretation of the outputs in terms of dominating factors.

Estimating recharge over years has been carried out in different areas using different methods. Whereas one method can be applied for local specific studies, another can better in regional studies; one method can be better in representing recharge values on time scales that range from daily, monthly, yearly and more other much longer from decades to thousands of years (Xu et al., 2018).

Studies for example; Leketa et al., 2019; Nyagwambo, 2006 and Watson et al., 2020 used chloride mass balance (CMB) method with a combination of other methods such as, the daily catchment water balance (WB), the water table fluctuation (WTF) and Base flow Separation method (BFS) to estimate groundwater recharge within Southern Africa. Results indicated a high spatial variability in estimated recharge though some methods yielded a close range of recharge values. These studies furthermore highlighted the importance of combining hydro chemical tracer methods with numerical modelling in data-scarce catchments to fully understand the nature of recharge dynamics.

Xu et al (2018) suggested that methods for example, Equal Volume Spring Flow (EVSF), Chloride Mass Balance (CMB), Rainfall Infiltration Breakthrough (RIB), Extended Model for Aquifer Recharge and moisture Transport through unsaturated Hard rock (EARTH), Saturated Volume Fluctuation (SVF), Water Table Fluctuation (WTF) and Groundwater Modelling

(GM) can be used in arid and semi-arid regions with greater certainty. However, among these methods, CMB remains the most used method compared to GM.

In most of these studies, efforts have been made to determine recharge rates mainly for water supply purposes, for contaminant transport or aquifer vulnerability on global, national, and regional scales. Additionally, most of these studies use various groundwater recharge estimation methods for purposes of water resource management especially considering the high variability at local scales. However, local, and intermediate scale assessments are also critical for integrated water resource assessments and management.

Uitenhage Artesian Basin (UAB) is a topographic catchment area in which a major artesian aquifer has been found. The aquifer is known to supply approximately 1400 million litres of water per year for agricultural, domestic, and industrial uses within the Uitenhage area (Baron, 2000; Maclear, 2001; Nyawo, 2017). The study area is the upper portion of the larger UAB catchment, where groundwater recharge of the aquifer is understood to occur because of its upslope of the confined portion of the aquifer.

In the study, “the upstream area” is referred to as the study area. Like in many other African catchments, there exists limited quantitative knowledge about groundwater recharge dynamics in the upstream area. Additionally, very few holistic studies that integrate groundwater recharge dynamics and surface water estimation methods in a qualitative approach in the UAB have been done (Maclear, 2001).

A study by Hughes (2010a) expressed the importance of using all the available information to better understand groundwater recharge dynamics. To provide the information needed for sustainable water resource management, using holistic approaches in estimating groundwater recharge volumes is paramount. Thus, the current study’s objective is to use holistic approaches to obtain recharge estimates for upstream recharge areas feeding the UAB by applying a conceptual-perceptual model together with two numerical hydrological models (Modified Pitman and SWAT).

1.2 Statement of the problem

Groundwater has become an important water resource globally (Dekongmen et al., 2022). However, overexploitation has resulted in depletion and quality degradation among other problems in numerous parts of the world. Uitenhage Artesian Basin (UAB), an important groundwater artesian basin in South Africa, is no exception (Baron, 2000; Maclear, 2001). In UAB, due to the increase in groundwater abstraction from boreholes to meet the increasing water demand, Piezometric depths are increasing leading to changes in artesian pressure conditions (Maclear, 2001). Addressing these problems, common to artesian basins globally, requires a holistic approach to estimating groundwater recharge.

Even though groundwater recharge is a critical hydrological variable, its accurate measurement remains a difficult task, particularly in semi and arid environments (Beekman; et al., 2003; Nolte et al., 2021; Parsons, 2014; Xu et al., 2018). Furthermore, the heterogeneity of groundwater recharge coupled with different recharge estimation methods mean that different studies of the same area frequently provide notably different groundwater recharge values for example (Wu, 2005) obtained different recharge estimates in Kammanassie area while using mixing model of chloride mass balance, cumulative water level departure, regression of cumulative spring flux and water balance methods respectively.

The differences in the estimated groundwater recharge may be attributed to various factors which include using physical parameters that are not very exact, modelling with no field measurements, generalisation of the catchment natural processes, using different process assumptions among others. These factors have resulted in groundwater resources being poorly understood, undervalued, mismanaged, and even abused and to overcome this challenge, different authors for example (Leketa et al., 2019; Nyagwambo, 2006; Wu, 2005; Xu et al., 2018) have promoted the use of multiple recharge estimation methods.

Although UAB has been locally well-researched in terms of hydrogeological characteristics, there remains an insufficient understanding of the upstream groundwater recharge dynamics of the basin. The upstream area consists of Table Mountain Group (TMG) quartzitic sandstones, which form a section of the Groot Winterhoek, Elandsberge, and Zunga mountain ranges (Baron, 2000; Maclear, 2001; Nyawo, 2017). The TMG is known for high recharge volumes and deep groundwater flows due to its highly folded and fractured nature. Thus, understanding the dynamics of the TMG recharge zone is key to understanding the impacts associated with extensive groundwater use downstream in the UAB.

To understand the recharge dynamics of a particular area, scholars and scientists recommend the application of a variety of methods, and hydrological models are one of the key methods, which can be used (Dunn et al., 2008; Pande et al., 2012). However, there is still a challenge in selecting suitable hydrological modelling tools for use in groundwater recharge estimation (Nolte et al., 2021; Tanner, 2013). The current study, therefore, aimed to explore and address this issue for the UAB by applying holistic approaches to understanding groundwater recharge dynamics using knowledge from previous research in the area, especially the studies of Baron (2000) and Maclear (2001,1996), in combination with the application of the modified Pitman and SWAT models and other published information.

1.3 Research objectives

1.3.1 General study objective

The overall study objective was to evaluate the application of the Modified Pitman model and Soil Water Assessment Tool (SWAT) model for groundwater recharge estimation in the upstream area of Uitenhage Artesian Basin.

1.3.2 Specific Objectives

- i. To design a conceptual-perceptual model to be used in understanding groundwater recharge dynamics and setting up the numerical hydrological models in upstream area.
- ii. To estimate groundwater recharge using all available data together with the Modified Pitman and SWAT models in the upstream area.
- iii. To compare the outputs of the two numerical models to one another and to local studies.

1.4 Research Questions

- i. Using the two numerical models, how much of the annual precipitation received in the upstream area is recharged to groundwater?
- ii. To what extent can the use of Modified Pitman model be relied upon as an appropriate practical method for estimating groundwater recharge considering its simplicity?
- iii. How well do the two numerical models differ in estimating groundwater recharge?

1.5 Justification of the study

Uitenhage Artesian Basin (UAB) is considered among the biggest and most significant confined aquifers providing water supply to the Uitenhage area (Maclear, 2001; Nyawo, 2017; Parsons, 2004). Understanding the upstream area recharge dynamics of UAB will provide

information to water resource managers and practitioners to facilitate better-integrated water resource management assessments and to equitably allocate water to different players in the basin while maintaining the required environmental standards.

1.6 Significance of the study

The study is aimed at contributing towards the improvement of groundwater resources management by providing holistic way through a general approach of making use of available data as well as numerical models (model Intercomparison and method comparison) to understand groundwater recharge dynamics in various similar basins such as UAB. Information on the groundwater recharge dynamics can be used in the integrated management of water resources, planning for withdrawals across various users in different sections of catchment or basin and the sustainable use of various environmental services delivered by the watershed. Information on groundwater recharge characteristics and their spatial and temporal patterns in the UAB, can be used by water resource managers, disaster management boards, irrigation boards, industries, and the local inhabitants to facilitate better management and conservation of the basin.

1.7 Conceptual Framework

In current study, an attempt was made to evaluate the application of the two selected hydrological models for estimating groundwater recharge in the upstream area of UAB. The study followed the framework presented in Figure 1.1. The dependent hydrological variable is groundwater recharge, which is influenced by various factors such as lithology, geology, vegetation, soils, elevation, and climate. The study first developed a conceptual-perceptual model which was aimed at building a better picture of the upstream area recharge dynamics. Secondly, the study used the Modified Pitman and SWAT models together with all available data to quantify groundwater recharge. Lastly, the study compared the outputs of the two numerical models to one another and with local study results. Specific details on data and analysis methods adopted to achieve the specific objectives are presented in chapter four under methodology.

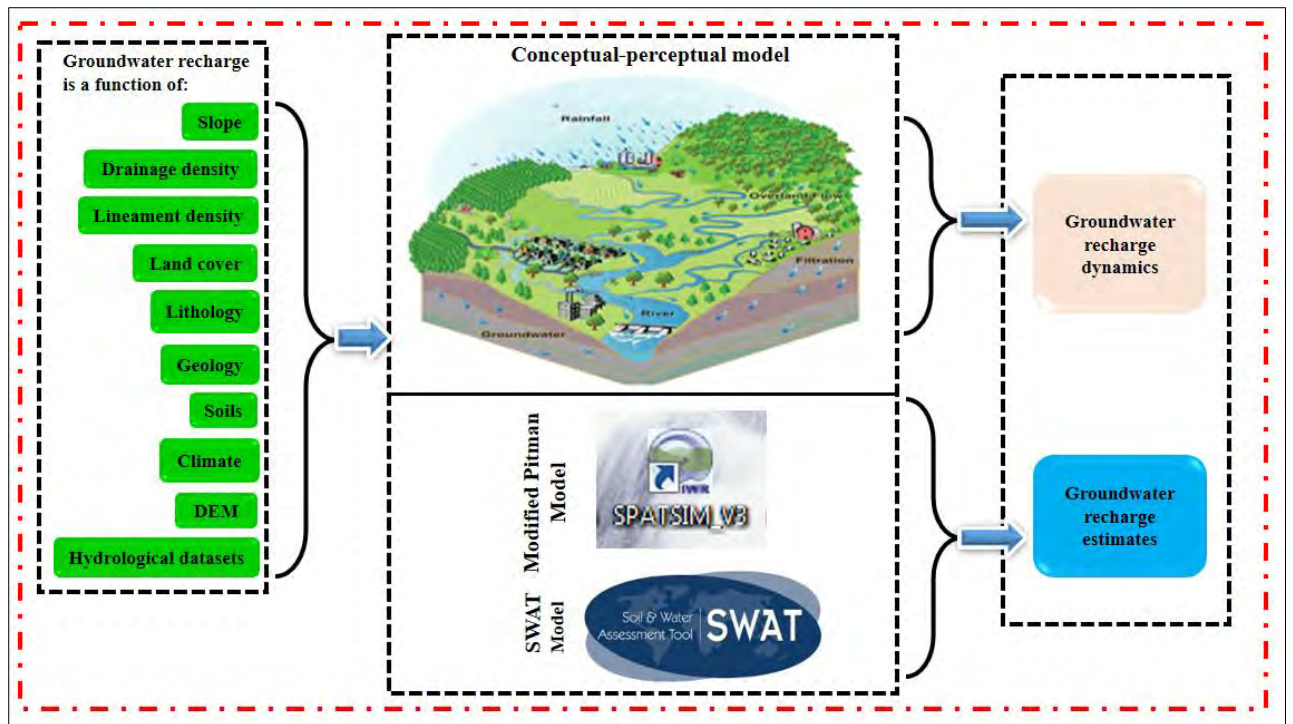


Figure 1.1. Conceptual framework for the study

1.8 Structure layout of Thesis

Chapter 1: Gives the general overview and background of groundwater resources, problem statement, objectives, research questions, relevance, conceptual layout, and structural layout.

Chapter 2: Reviews literature on: Groundwater-surface water resources assessment and management in South Africa, modelling surface-groundwater interactions, an overview of hydrological modelling types and structures, overview of the conceptual-perceptual model, overview of groundwater recharge assessment and management in Southern Africa, the Modified Pitman Model, the SWAT model and contextualizes them to the study objectives.

Chapter 3: Gives an overview of key characteristics of the study area such as, climate, geology, and soil, among others. **Chapter 4:** Describes the methodology used in the study, details the data used and its sources, gives a brief description of the catchment-based conceptual-perceptual model developed using all available data, and the two numerical hydrological models used. It goes on to describe the methods used to assess the value of the application of the two hydrological models. **Chapter 5:** Presents and discusses the results obtained from the assessments. **Chapter 6:** Concludes research findings, provides recommendations with suggestions to be applied in other new investigations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

About 30 % of the world’s liquid freshwater exists as groundwater (Figure 2.1), from which many communities draw to meet various needs (Bouchet et al., 2019; Dekongmen, et al.,2022; Döll et al., 2012; Jia, 2007; Parsons, 2004; Watson et al., 2021). Since the water stored in icecaps and glaciers is not easily available for general consumption, groundwater remains the largest source of freshwater available to man (Woodford et al.,2002), and its uses are forecasted to increase, particularly in areas where surface water supplies are becoming insufficient (Bonsor et al., 2018; Chinnasamy et al., 2015; Hughes, 2019b; Vörösmarty et al., 2005).

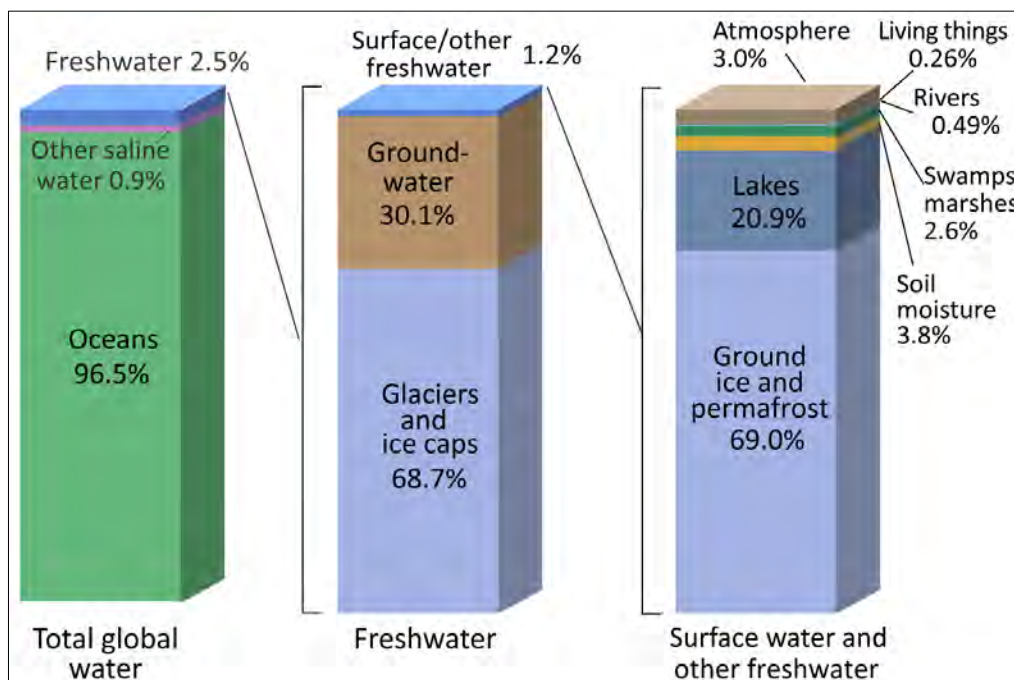


Figure 2.1 Distribution of Earth's water bodies (Credit: U.S. Geological Survey, Water Science School)

In South Africa, some areas still regard groundwater as unreliable source of water just because its contribution to the national water budget is estimated to be at 10% (Woodford et al.,2002), which brings significant challenges to sustainably allocate the limited water resources to support the ever increasing economic growth and development of South Africa (Mander et al., 2017; Pitman, 2011; Schreiner et al., 2010; Thopil et al., 2016). Nolte et al (2021) indicated that, the growing demands for water and increasing occurrence of droughts require a diversification of sources of water supply to enhance water supply security consequently,

groundwater can be thought of as a reliable and economic source of water. In the same line, Leketa et al (2019) stated that, regions whose climate is characterized as semi-arid or arid, groundwater is usually the driving force behind their economic development and the main source of water supply as the local surface water bodies are usually ephemeral.

On the other hand, as surface water resources are now being exploited almost to their limits coupled with increasing pollution and climate change impacts, South Africa is making efforts to efficiently use its groundwater resources now and in the future to meet the water demand amidst other challenges especially in the dry areas, that cover approximately 66% of the country, with no major rivers, or abundant surface water sources (Nolte et al., 2021; Sami and Hughes, 1996; Woodford et al., 2002).

Although there seems to be a wealth of data in terms of climatological and river discharge time series within South Africa, knowledge on groundwater both at local and regional scales is still scarce or highly generalized, a fact that is partly attributed to the complexity of various aquifers which are fractured and highly heterogeneous (Abiye, 2016; Nolte et al., 2021; Parsons, 2014; Woodford et al., 2002). Nevertheless, it should be noted that groundwater resources have and are still playing a significant role in the development of South Africa, for example, many cities, towns, mines and irrigation schemes have developed because of the continuous supply of water from groundwater sources (Abiye, 2016; Kelbe et al., 2010; Leketa et al., 2019; Pitman, 2011; Woodford et al., 2002) and thus their assessment is of national importance (Parsons et al., 2001; Woodford et al., 2002).

2.2 Groundwater recharge dynamics

As reported by different authors, for example, Nolte et al., 2021 and Walker et al., 2019, groundwater resource exploitation in many parts of Africa and its vital roles are predicted to increase soon. Across the globe, groundwater resources are regarded to be among the indicators one can use to assess the likelihood sustainable development of a given country since they can provide water that requires little or no treatment in areas which are insufficient of rainfall and surface water resources (Hughes, 2019, 2014; Izady et al., 2014, 2012; Ndhlovu and Woyessa, 2021; Tanner, 2013; Xu et al., 2018). For groundwater to be readily available as a sustainable source of water for economic development, there has to be significant known estimates of recharge to groundwater (Leketa et al., 2019). Abiye (2016) suggested that, known

groundwater recharge estimates may provide a better understanding of the resource and its optimal management strategy.

Despite numerous advances in hydrology and relevant technology, recharge estimation remains challenging, particularly in dry areas (Beekman; et al., 2003; Mutoti, 2015; Nolte et al., 2021; Parsons, 2014; Sami and Hughes, 1996; Xu et al., 2018). It is because groundwater recharge fluxes in these areas are usually low when compared with received annual rainfall (Martinez et al., 2015; Watson et al., 2020). Additionally, other spatial-temporal varying factors, such as vegetation cover, climate, soil, topography among others, complicate proper assessments of groundwater recharge since it takes place through a complex nexus of these factors (Abiye, 2016; Lerner, 1990).

2.2.1 Definitions of groundwater recharge

There exist slight differences in the definitions of groundwater recharge across authors. However, Lerner et al (1990) explicitly defined groundwater recharge as direct (direct infiltration of precipitation and percolation through the unsaturated zone to a groundwater body), indirect (percolation to the water table through riverbeds) and localized recharges (accumulation of precipitation in surface water bodies, and subsequently concentrated infiltration and percolation through the unsaturated zone to a groundwater body). In the current study groundwater recharge definition according to Parsons (2004), “where water comes from processes of infiltration and percolation from all forms of precipitation into groundwater store systems” was adopted.

2.2.2 Mechanisms of groundwater recharge

De Vries et al. (2002), classified three classes of groundwater recharge in their study which include direct recharge (precipitation and infiltration), indirect recharge (rivers and infiltration) and localized recharge (joints, depressions, fractures, infiltration) (Figure 2.2). These classes are also such as those that were explicitly defined by Lerner et al (1990). According to Abiye (2016), groundwater recharge mechanism occur through a complex network of soil and rock structures in the form of residual rainfall and depends on the physical nature of an aquifer system rather than rainfall amount. An attempt to understand groundwater recharge mechanism, fate and flow dynamics is thus vital for the proper estimation of recharge of an area (Leketa et al., 2019).

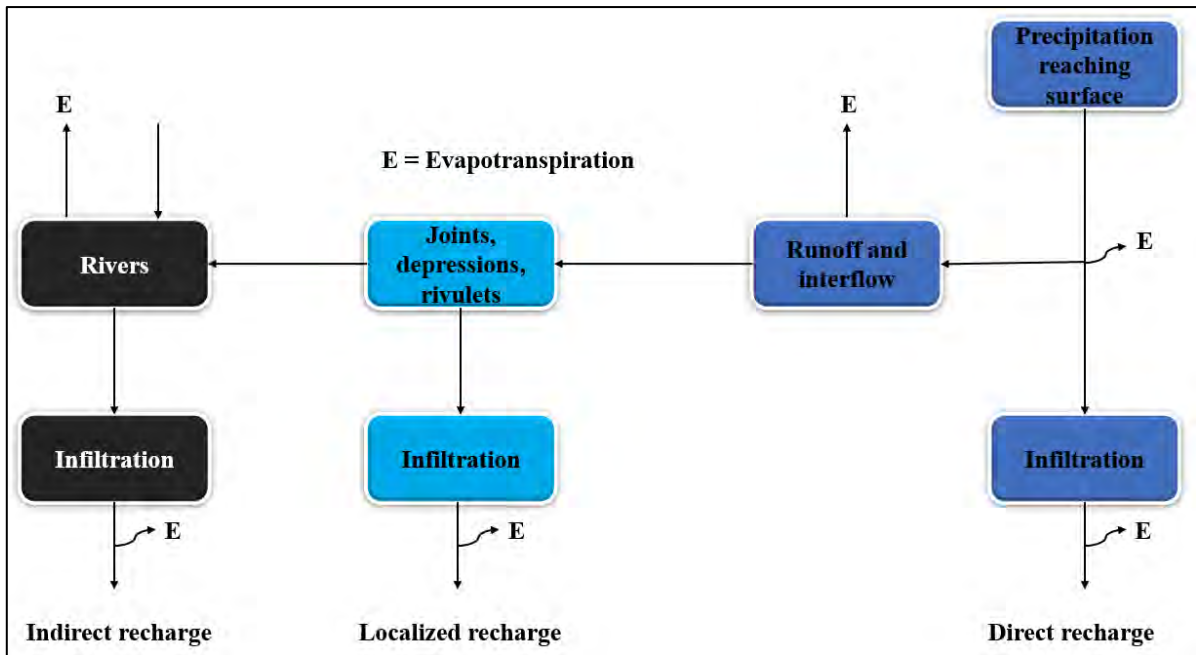


Figure 2.2. Various groundwater recharge mechanisms for a semi-arid area (Adapted from De Vries and Simmers, 2002)

2.2.3 Surface water-Groundwater interactions

Surface water-Groundwater interaction (SW-GW) is a purely natural and partially anthropogenic catchment driven process which involves exchanging water between surface water bodies and groundwater aquifers in the direction that depend on relative water levels, heads and the connectivity of different materials (Tripathi et al., 2021). The interaction can be viewed in two different forms, such as surface water to groundwater (SW-GW); where rainfall can recharge groundwater directly but also water that instead become surface runoff and shallow subsurface runoff can enter a surface water body and recharge groundwater via riverbeds, floodplains and lake plains, groundwater to surface water (GW-SW); it happens when groundwater head is higher than the topography, intersected by the riverbed or a depression, and the material medium separating the two is permeable. This will make groundwater to flow into surface water body (Parsons, 2004; Tanner et al., 2015).

It should be noted that the rates and directions of exchange between the two water resources can change over time in some places due to several factors. Hughes (2010) stated that the interaction may be relatively straight forward in humid areas since it often takes place close to the ground surface as compared to arid areas where the separation depth is often high, and the interactions become difficult to be observed with simple mechanisms. Additionally, Tripathi

et al (2021) demonstrated that the complexity of the interaction pose a challenge to characterise it with a high level of certainty due to differences associated with it.

2.3 Overview of groundwater recharge assessments in Southern Africa

The shortage of surface water supplies in areas with unreliable and highly varying precipitation has meant groundwater to become a vital alternative water supply to many dry places across the world that have reasonably favorable hydrogeology. Fernández-Mejuto et al (2021) stated that, there is still a problem of limited understanding of aquifer systems and groundwater recharge, and these could hamper both regional and local sustainable groundwater resource management.

In South Africa, authorities that manage water resources started recognizing the principle of public and private water associated with riparian rights in 1998 (Kelbe et al., 2010). With groundwater not being considered a major water resource at that time, nearly all nationals were using surface water resources. In most parts of South Africa, groundwater was not considered to be of adequate importance (Woodford et al., 2002), and was classified as private water with the rights to it linked to land ownership. The necessity to improve sustainable water resource management strategy in South Africa was recognized many years ago, though it only happened when new legislation was introduced in 1998 that recognizes all water as one entity (Kelbe et al., 2010).

According to Xu et al (2018), there have been various studies on recharge estimation in most Southern African countries over the past four decades, with fewer done in Zimbabwe and Zambia. In the case of South Africa, government groundwater recharge assessments were first done in the early 1970s, in the Northern Cape (Beekman et al., 2003; Wu, 2005; Xu et al., 2018), and during that time groundwater recharge assessments were operated on a local scale to serve data needed for larger projects (Xu et al., 2018). South Africa realized the need to develop methods so that it can maintain groundwater resources sustainably after the outcomes of the 1987 Turkey International Groundwater Recharge Workshop (De Vries et al., 2002; Xu et al., 2018).

2.3.1 Groundwater recharge estimation methods in Southern Africa

It is difficult to measure groundwater recharge accurately and the methods used can vary considerably, even for the same region (Nolte et al., 2021; Tanner, 2013). Groundwater recharge has been estimated using various methods, which vary with catchment processes

(Abiye, 2016; Arnold et al., 2000; Crosbie et al., 2005; Dekongmen et al., 2022; Hughes, 2004b; Hughes et al., 1993; Maclear, 2001; Scanlon et al., 2006, 2002; Wang et al., 2008; Watson et al., 2018). Xu and Beekman (2003) discussed and identified challenges in the application of the various recharge estimation methods in Southern Africa and their study identified the most promising methods for recharge estimation and these are; the Chloride Mass Balance (CMB), Cumulative Rainfall Departure (CRD), Extended model for Aquifer Recharge and moisture Transport through unsaturated Hardrock (EARTH), Water Table Fluctuation (WTF), Equal Volume Spring Flow (EVSF), Groundwater Modelling (GM), Saturated Volume Fluctuation (SVF), Rainfall Infiltration Breakthrough (RIB) and Hydrograph Separation (HS) methods.

Some of the methods are based on mass balance of selective constituents and use numerical analysis. And those that depend on mass balance, rainfall relationships, and water level fluctuations have proved to be robust in estimating groundwater recharge compared to other methods, though EVSF together with CMB have been widely used in most regions of Southern Africa and are recommended by many authors (Xu et al., 2018). Abiye (2016) suggested that care must be taken when selecting a given method to use while estimating groundwater recharge since many available methods have their own drawbacks with associated different margins of errors emanating from parameter estimation, spatial coverage of the processes among others.

Many methods demand a great deal of data which is usually unavailable (Chand et al., 2004). However, Scanlon et al (2002) demonstrated that models can provide an alternative method for estimating groundwater recharge, even in areas which are very dry and have complex environmental characteristics since they can incorporate a variety of factors and processes governing recharge. Thus, the current study aims to apply holistic approaches in understanding groundwater recharge dynamics for the upstream area of the UAB using the modified Pitman and SWAT models.

2.3.2 Previous groundwater recharge studies within TMG area in South Africa

Local groundwater recharge estimation studies have been carried out in South Africa especially in areas which are dominated by Table Mountain Group (TMG) with UAB inclusive (Wu, 2005). These studies and their findings are used as a background on the current study site and their local data (Table 2.1) to inform the modelling process in the current study.

Table 2.1. Review of recharge estimates in some of TMG area (Adapted from Wu, 2005)

Place	Method	Aquifer	MAP (mm)	RE (%)	Author
Uitenhage Artesian Basin	Spring flow		298.2-1202.6	10	Kok,1992
	CMB	Groot	523.3	25	Maclear,1996
	CMB	Winterhoek		55	Parsons, 2002
Whole TMG (with radius of 200km form Cape Town)	GIS	13200Km ² outcrop	600-2020	33	Weaver & Talma, 2002
Uitenhage, Coage aquifers	CMB		250-850	24-55	Maclear,1996
	WB			11	Bredenkamp,2000; Xu and Maclear, 2003

CMB: Chloride Mass Balance; GIS: Geographical Coordinate System; WB: Water Balance

2.3.3 Groundwater and Surface water resources assessment and management in South Africa

Knowledge about interactions between groundwater and surface water within many basins is still insufficient for many surface and groundwater hydrologists and yet these interactions provide key information required during operative water resource assessments (Hughes and Parsons, 2007; Parsons, 2004; Tanner et al., 2019, 2015). In the past, surface and groundwater resources were isolated in the South African policy and regulation (Act 56 of 1956), with groundwater less centrally managed and rights to use it were tied to land ownership (Jumbi et al., 2018; Mander et al., 2017; Nolte et al., 2021; Tanner, 2013; Woodford et al., 2002).

Parsons (2004) argued that incorrect usage of interaction as a terminology was also among the greatest challenges to develop a better understanding of surface-groundwater interaction within South Africa. It made management of the two resources differently in many water resource feasibility studies a consequence that resulted into lack of integration assessments of the two resources and hindered the development of conjunctive use of these resources (Nolte et al., 2021). Those that tried, quantified them separately and then summed them with an assumption that the summation represents the total supply that is potentially available for an area, not realizing that they impact one another (Parsons, 2004; Tanner, 2013).

Previously, water managers in South Africa focused on the estimation of the yield from relatively large reservoirs, while more recently there has been a shift to integrated management of surface and groundwater as well as accounting for environmental water requirements (EWR) (Hughes and Parsons, 2007; Kapangaziwiri et al., 2011). As issues related to water quality, quantity and equitable allocation of water resources emerged, the desire to understand the linkages and manage the two resources together became clear (Parsons, 2014, 2004; Pitman, 2011; Tanner et al., 2019, 2015; Winter et al., 1999). In addition, the recent Water Act (Act 36

of 1998) required all water resources to be managed in a holistic and integrated fashion (Kelbe and Germishuysen, 2010; Tanner, 2013).

The more recently produced databases from the DWA-South Africa and various recent studies for example, Döll et al., 2012; Martinez et al., 2015; Nyawo, 2017; Parsons 2014 and Spinoni et al., 2014, have incorporated the two water resources for better understanding and assessments, however, it does not mean that the interaction between them is acknowledged or clearly understood.

2.3.4 Groundwater-surface water interaction assessments

There exist numerous methods which are either direct or indirect (hydrological, hydrogeological, tracer, GIS-based and geophysics based) available to assess, characterise and quantify the interactions between surface and groundwater in South Africa, however, each of these methods is associated with strengths and limitations Tanner (2013). Methods applied at a larger scale such as baseflow separation, hydrogeologic mapping, vegetation mapping and ecoregion classification, groundwater modelling, hydro-chemical and stable-isotope analyses are more appropriate than their counterparts (Levy and Xu, 2011).

In the same regard, Parsons (2004) proposed the usage of base flow method as the approach would be compatible with the hydrograph separation method in South African context. In the same line, Levy and Xu (2011) state that estimating average annual fluxes at the scale of fourth-order catchments with base flow separation techniques and then subtracting the groundwater discharge rate from the recharge rate is the appropriate approach to be used to assess the interactions of the two resources in South Africa. Although the approach may ignore spatial-temporal variability and potentially missing local impacts.

Kelbe and Germishuysen (2010) conducted a study in Maputaland and gave detailed analyses of the different methods that are suitable to assess surface and groundwater interaction in South African context, the methods include; mass balance, hydrostratigraphic unit, storage and yield, hydraulic conductivity, GIS and numerical modelling, however, the authors stated that numerical modelling is the most pragmatic approach to describe and assess the interaction in many South African catchments given their complex geology and data availability issues.

In addition, the models used for catchment water resources assessment have been further developed to represent SW-GW interactions in more sophisticated ways as our understanding has grown. It should be noted that from the various assessment methods done in South Africa,

there still exist insufficient knowledge about the kind of interaction that is occurring, when, and by how much and thus, it is so imperative when selecting the method to be applied in the case study area, to first consider the study aim and objectives.

2.4 Overview of qualitative conceptual-perceptual models

In the field of hydrology, models are considered principal tools of modern research and assessments. Here, they have been used to incorporate human knowledge and understanding of hydrological systems in ways that allow human beings to understand the ability and functions of the natural system for further analyses (Beven, 2019, 2011; Bredehoeft, 2005). However, the foundation of any hydrological model explicitly depends on the conceptual-perceptual knowledge of processes involved in each catchment (Cornelius et al., 2019; Savenije, 2010).

There has been confusion among hydrologists and hydrogeologists about the definition, usage, and application of the term qualitative conceptual models (conceptual-perceptual) and numerical conceptual models such as rainfall-runoff models (e.g., Pitman (Hughes, 2013)). This confusion has made hydrological and hydrogeological modellers miss out on some of the most important aspects for example preferential recharge flow which are not easily detected and modelled by numerical models for a given catchment or basin.

Important to note in the current study that, the term conceptual-perceptual model refers to the same concept and not referring to a numerical model in which the algorithms are on the more empirical side of the spectrum, but rather it is on the side where it forms an easy expression of natural system operations; and thus, in this case, it is used to build numerical models by translating into equations and algorithms (Cornelius et al., 2019; Izady et al., 2014).

2.4.1 Definitions of conceptual-perceptual model

Numerous authors have given alternative definitions of a qualitative conceptual model. For example, Bredehoeft (2003) defined it as a scientific integration of knowledge while (Cornelius et al., 2019) defined it as one that depicts what is known or assumed regarding how water moves across the landscape, the processes involved, flows, and connections that are depicted in the form of diagrams, flow charts, and texts. Izady et al (2014) described it as a visual depiction of hydrological processes, and it is made of justified and simplified assumptions which capture key elements of a natural system to better understand its behaviour. Walker et al. (2019) stated that qualitative conceptual models visually represent interconnectedness within groundwater and surface water systems in simple diagram formats (Figure 2.3).

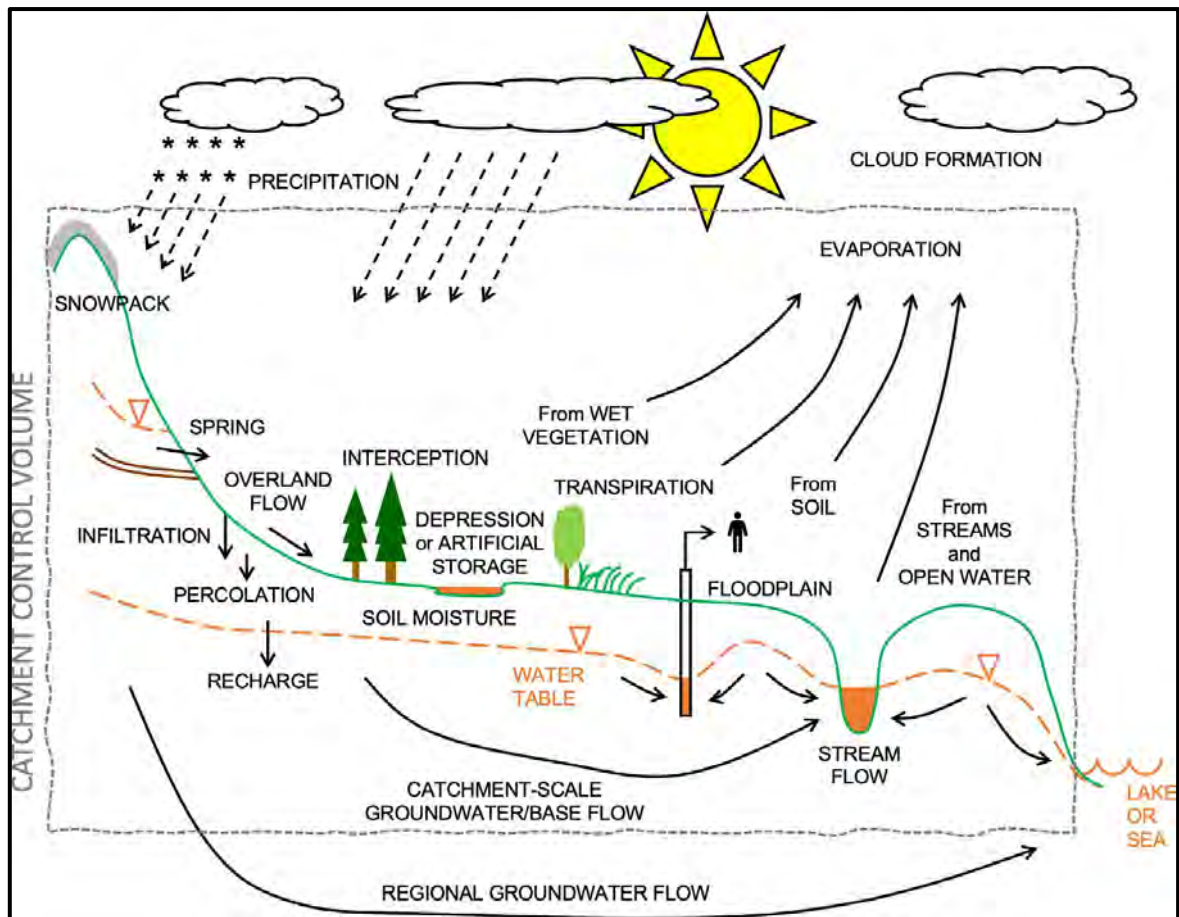


Figure 2.3. A simple illustration of a conceptual-perceptual model

2.4.2 Conceptual-perceptual models in hydrological environment

Since hydrological systems are complex, qualitative conceptual models can act as a precondition before setting up any numerical predictive model (Rivera, 2007). They can help to constrain the uncertainties and manipulability associated with numerical models (Beven, 2011; Brassington et al., 2010). Additionally, since numerical models are prone to epistemic uncertainties which can give birth to equifinality (Beven, 2019; Hughes, 2010a), conceptual models on the other hand help to align the outputs of these numerical models better and therefore reduce uncertainties inherited with numerical models (Beven and Chappell, 2021). Comprehensive interpretation of various processes contained within a natural system can help to make numerical models more realistically evaluated (Tanner, 2013).

Representing processes with equations and parameters of hydrological systems into a scientific arena is one of the complex problems in hydrological modelling (Bredehoeft, 2005). The complex problem, however, can be solved by developing qualitative conceptual models. Developing these models involve assessment of existing topography, geology, lithology, land

use/cover, reviews and analyses of existing hydro-meteorological data, stakeholder observations about hydrological events and processes (citizen science), field investigations, laboratory analyses, existing and overlapping published research in the study area which all generally have varying degrees depending on the study site location (Brassington et al., 2010; Gao, 2015; Walker et al., 2019). The amalgamation of these datasets leads to an integrated and robust qualitative conceptual model which then leads to proper numerical model modifications (Cornelius et al., 2019).

2.4.3 Conceptual-perceptual model applications in South Africa

Hughes, (2010a) recognized the vital role of all available information within the hydrological modeling spectrum, however, in many African countries with South Africa inclusive, there still exists limited quantitative knowledge about surface and groundwater recharge (Tanner, 2013; Hughes, 2004). Additionally, very few holistic contributions have been made to integrate groundwater recharge dynamics and surface water estimation methods in a qualitative approach (Hughes, 2004; Sami et al., 1996).

On the other side, numerical modelers usually assume that certain processes are occurring in isolation from other micro-scale processes, for example they assume infiltration-percolation processes only occur at soil field capacity forgetting preferential recharge flow path patterns from fractured structures. In dry places such as South Africa, however, localized-preferential recharge is expected to dominate during strong storms and can counterbalance deficits in soil moisture thus causing direct groundwater recharge through the soil layers (Hughes, 2010; Sami et al., 1996).

Savenije et al (2017), noted that models of catchments commonly miss essential characteristics that determine their functionality and that, to clearly improve their performance, they should be directly linked to the conceptual-perceptual analysis of critical aspects of the catchment processes. However, catchment-scale processes are complex, even though numerical tools are modified on grounds of reality representation in a qualitative conceptual format (Hughes and Mazibuko, 2018). It thus, renders a need to integrate qualitative conceptual models with numerical models to bridge data scarcity issues, especially when accounting for the small-scale processes, for example localized recharge which is key in understanding surface and groundwater recharge dynamics.

To better understand surface water-groundwater interactions, requires the use of an all-inclusive approach that can help in integrating the drivers of recharge and discharge dynamics of a given catchment (Hughes, 2010; Sami et al., 1996; Tanner, 2013) and this approach is a qualitative conceptual model which the current study is sought to develop.

2.5 Overview of numerical hydrological modelling types and classes

Silvert, (2007) defined a model as one that shows a natural or artificial system in form of a physical, analogic, or mathematical environment. Additionally, a model can be used to refer to a specific model set-up of a given catchment, and a “modelling tool” for the software one could use to make and run a model at the same time can be used to underpin all hydrological processes that are under study (Dunn et al., 2008; Gupta et al., 2008; Milad, 2012). According to Akoko et al (2021), there has been a steady dominance over time in the use of computer models with or without field data in many hydrological assessments since they offer numerous advantages such as, economic savings, and spatio-temporal representation of complex micro-scale processes among others.

2.5.1 Model based classification

Models can be broadly classified as algorithms (approaches), spatial discretisation (structure) and parameterisation (parameter and output) based.

a) Algorithm based models

Empirical models

These models make use of existing data obtained from observations to mathematically describe catchment process outcomes (Pechlivanidis et al., 2011). They are empirical in nature, and they include Data-Based Mechanistic models (DBM) and Artificial Neural Networks (ANN) (Wheater, 2002). Their simplicity has allowed them to be used in catchments without in-situ measuring points to extrapolate extreme events. However, they require a lot of observational data, including observations of the desired output variable(s), and their results remain debatable as they don't give detailed information about the internal catchment processes (Wheater, 2002).

Conceptual numerical models

Conceptual numerical models make use of conceptual representation of key aspects that are vital in understanding processes within a given catchment (Milad et al., 2012; Pechlivanidis et al., 2011; Wheater, 2002). They came into use during the last five decades when computation

power started improving (Wheater, 2002). Conceptual numerical models' parameters don't have any direct physical measured identity, implying that model parameter values are obtained in the process of calibration (Dunn et al., 2008; Pechlivanidis et al., 2011; Wheeler, 2002). A comprehensive understanding of these models has been further discussed by various authors for example, Attandoh et al., 2013; Bredehoeft, 2005,2003; Gupta,2008; Herbert and Döll, 2019; Hughes, 2009; Izady et al., 2014; Milad et al., 2012; Mkali, 2020; Tanner, 2013; Wagener et al., 2008 and Walker et al., 2019.

Physics-based models

These kinds of models depend on a physical understanding of hydrological processes occurring at a given catchment (Wheater, 2002). Modelling with the current approach became feasible during the last four decades when there had been sufficient advancement in computing technology. The model represents a hypothesis about processes and an opportunity to test it within the catchment under consideration (Wheater, 2002). Physics-based models can be utilized in catchments without observational measuring points and can simply represent changes within the catchment if the physical parameters have been determined (Milad et al., 2012; Pechlivanidis et al., 2011; Wheeler, 2002).

However, the extrapolation of analyses associated with these models at larger scales involves representation of processes that may solely depend on non-observational measuring points which may raise issues of equifinality (Beven and Chappell, 2021; Hughes and Mazibuko, 2018; Savenije and Hrachowitz, 2017; Wrede et al., 2015). Additionally, the scales at which different processes operate or dominate or can be measured in the field are heterogeneous making it difficult to obtain observations and make reasonable assumptions about certain processes that can be generalised across scales (Pechlivanidis et al., 2011).

Hybrid models

Many models are commonly labelled as empirical, conceptual, and physic-based types; however, they include elements of two or more types. Hybrids encompass a combination of former models, and their developments were in response to reducing weaknesses associated with metric and conceptual models (Wagener and Kollat, 2007). Hybrid models conceptually represent processes, particularly where physical parameters are difficult to be measured (Orellana et al., 2008; Pechlivanidis et al., 2011).

b) Spatial discretisation

Lumped models

These are model types that represent a catchment as a singular unit (Beven, 2011, 2001; Milad et al., 2012; Savenije and Hrachowitz, 2017). These model types (Figure 2.4) are structured with various expressions, that do not consider the heterogeneity of the area but rather the homogeneity (Milad et al., 2012; Orellana et al., 2008; Savenije and Hrachowitz, 2017; Savenije, 2010; Singh, 2018; Tanner, 2013).

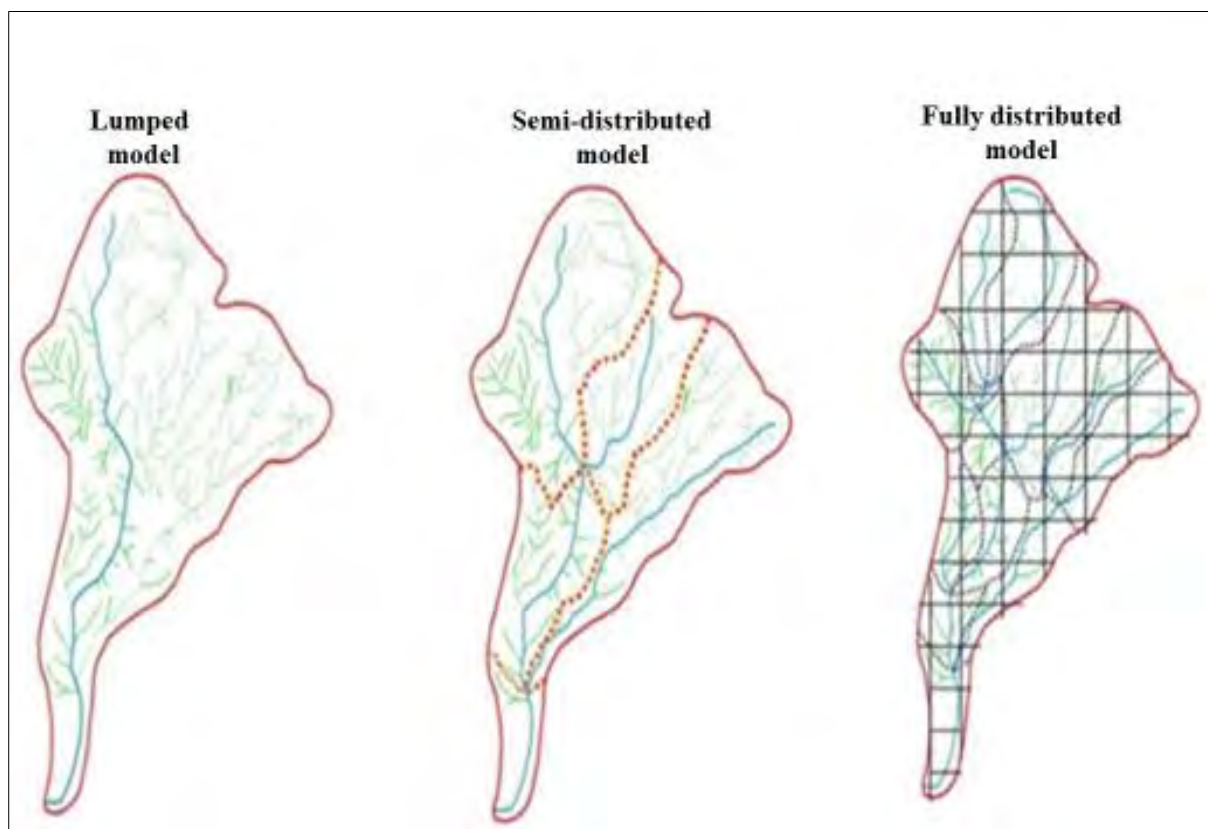


Figure 2.4. An illustration of lumped, semi-distributed and fully distributed models

Distributed models

These are models that make use of the heterogeneity of the study area, and they discretize it into smaller units to easily solve the state variables (Milad et al., 2012; Qu, 2005; Savenije and Hrachowitz, 2017; Singh, 2018) (Figure 2.4). They are, hence, capable of incorporating spatial variability into catchment hydrological processes, for example, data inputs, boundary conditions, and other catchment characteristics, although they average variables and parameters at the unit level (Savenije and Hrachowitz, 2017).

Semi-distributed models

These are model types that discretize the area (Figure 2.4) at a level of spatial arrangement of elements that are explicitly represented in a catchment (Qu, 2005), which can further be divided into sub-catchments that are different from each other and spatially arranged in a chronological order for instance; (upstream sub-catchments with downstream sub-catchments) which can be parallel to each other but feed in the same downstream area. They are also known to simulate well vital catchment processes using fewer data (Milad et al., 2012; Orellana et al., 2008). They can accommodate organizational features and their temporal evolution efficiently within the system (Beven, 2007; Milad et al., 2012; Orellana et al., 2008).

c) Parameterization based models

Deterministic models

These are models whose results are uniquely determined by looking at the relationships between data and state variables (Milad et al., 2012; Orellana et al., 2008; Pechlivanidis et al., 2011; Tanner, 2013). Parameter values are kept constant and so these models generate a single result with a single set of inputs per simulation.

Stochastic models

Stochastic models provide varied results per data input and as parameter values vary, using random variables to represent the process (Beven, 2001; Orellana et al., 2008; Pechlivanidis et al., 2011). Specific inputs may produce a result that follows a statistical distribution (Milad et al., 2012; Wagener et al., 2001). Due to uncertainties in input variables, boundary conditions, or model parameters, some randomness or uncertainty in the potential outcome is permitted.

Mixed deterministic-stochastic models

These are kinds of models whose design involve incorporating stochastic error models with deterministic models (Milad et al., 2012; Pechlivanidis et al., 2011; Wagener et al., 2001).

2.5.2 Modelling groundwater-surface water interactions

Hydrological models are used in many applications, particularly in the field of water resource assessments. Various limitations such as resource constraints and limited range of measurement techniques merged with limited spatial-temporal data have to a reasonable extent

hindered the use of these tools (Pechlivanidis et al., 2011; Watson et al., 2021). Nevertheless, the application of modelling technique has become an important tool in South Africa for purposes of assessing various water resources (Cornelius et al., 2019; Hughes, 2019a; Parsons, 2014; Savenije, 2010; Tanner et al., 2019; Watson et al., 2021).

Understanding processes associated with surface-groundwater (SW-GW) interconnectedness is emerging as an important aspect of managing and preserving resources and ecosystems (Conant et al., 2019). According to Kelbe et al., 2010 and Levy and Xu, 2012, numerical modelling appears to be the most pragmatic approach to describe and assess SW-GW interaction in South African when compared to other methods such as, field measurements (Barthel and Banzhaf, 2016).

The development and modification of models to simulate SW-GW interactions have resulted in the design of multiple models, with each one having different ways of analysing and simulating different processes that occur in SW-GW interaction and the processes simulated in the models can be explicit and implicit as stated by (Tanner, 2013). Tanner (2013) revealed that there are many key processes that need to be described when one is trying to understand SW-GW linkages. Models used to simulate these linkages can be categorized as simple and complex (Hughes, 2004; Tanner et al., 2019).

Typical groundwater models such as MODFLOW, FEFLOW among others were not used in the current study and rather the Modified Pitman and Soil Water Assessment Tool (SWAT) models which differ quite a lot in their approaches to model catchment processes were selected. While catchment hydrology models such as Pitman, SWAT and others may have started with a surface water focus, they have been developed to represent groundwater as well with need for conjunctive management of SW-GW, (Bouarfa and Kuper, 2012; Hughes, 2004a; Nardi et al., 2023; Rossetto et al., 2019) and as a result, they are becoming more full SW-GW representations as they include explicit calculations of recharge.

Specific groundwater models have often focused on groundwater flow direction, draw down from withdrawals, pollutant movement, among others and had relatively simple modelling of recharge or relied on people to work out recharge separately and input it into a modelling environment sometimes using more surface focused models such as SWAT. It is from the above augment that in the current study, the modified Pitman model and SWAT models were

selected since they include explicit calculations of recharge based on full SW-GW representations.

2.6 The Modified Pitman Model

A conceptual, rainfall-runoff and monthly time-based tool initially designed during the 1970s (original version) by Pitman, (1973). It has since been modified by (Hughes, 2004a) while preserving the basic model design to include simple groundwater routine components and other parameters for purposes of representing the natural processes that occur within a given catchment (Hughes and Mazibuko, 2018; Tanner et al., 2015; Tshimanga et al., 2011). Its design follows the principal design of most conceptual models, which involves using simple routines to represent dominant processes at the catchment scale (Hughes et al., 2006, 2002) (Figure 2.5).

The need to increase the model's capability to provide the required simulations for national and regional water resource studies in Southern Africa, and more broadly, triggered various modifications of the original model (Hughes et al., 2006, 2002; Tumbo et al., 2015). The original model structure represented all subsurface water in a single storage, without representation of vadose zone storage and interflow as separate from groundwater storage and flows. While capable of predicting monthly streamflow, the version did not generate the information needed to manage both groundwater and surface water resources, prompting the addition of the explicit groundwater representation (Hughes, 2013; Sami, 2006; Tanner, 2013).

The Modified Pitman model as of now, remains among the commonly applied models in Southern Africa, and some areas in Eastern Africa, as an appropriate method for assessing water resources to inform management (Bailey et al., 2016; Hughes, 2019a; Kapangaziwiri et al., 2013, 2011; Ndiritu, 2009; Tanner et al., 2015; Tshimanga et al., 2011).

2.6.1 Model structure

Structurally, the model is classified as a conceptual, rainfall-runoff, and monthly time-step model where independent parameters and other input variables required at the sub-basin level are determined by the modeller (Hughes, 2013; Tumbo et al., 2015). A detailed structure of the model can be found in (Hughes and Forsyth, 2006; Hughes, 2004; Tanner, 2013).

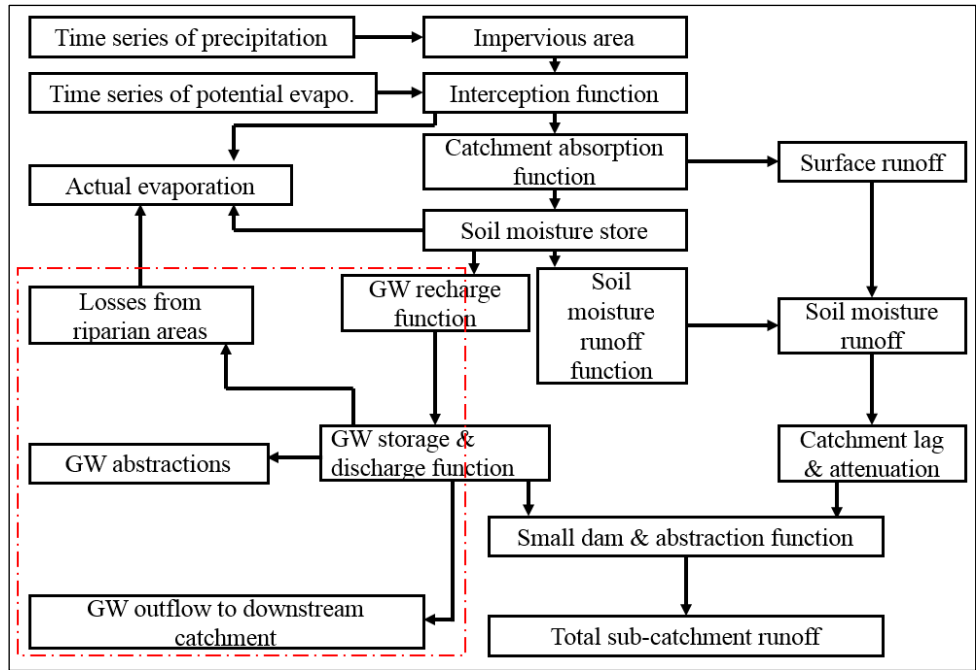


Figure 2.5. Structural diagram of the Modified Pitman model with groundwater routines enclosed within the dotted red rectangle (Adapted from Tanner, 2013)

2.6.2 Model parameters and setup

Modified Pitman model was developed with an awareness of data scarcity in many parts of Southern African and Africa at large, with the intention to base its structure on rigorous understanding of the conceptual simplification of catchment-based processes under study (Hughes, 2013; Tanner, 2013). The Modified version is powered by SPatial and Time Series Information Modelling (SPATSIM), a tool created at (IWR), Rhodes University-South Africa (Hughes and Forsyth, 2006). SPATSIM associates spatial data with various data types (data input, output, analysis routines) to the hydrological model (Tanner, 2013). Elements have been added to represent wetland as well as artificial structures such as small farm dams, larger reservoirs, and abstraction points (Hughes and Mantel, 2010). Various initial model run types, such as Single Run, Incremental Uncertainty Run, and Cumulative Uncertainty based on optionally stored sub-basin parameter sets, among others, can all be incorporated within the model (Hughes, 2004a).

For the current study, Institute for Water Research (IWR)-Rhodes University version of Pitman, (GWv3), (Hughes and Forsyth, 2006; Hughes, 2004a) that runs on SPATSIM was used given its famous application in Southern Africa, and some areas in Eastern Africa. The modified version is referred to in the model list as the; Global Options Threaded version three

(GWv3), (Hughes, 2013). This model version includes naturally explicit hydrological parameters and some other types required in water use distribution (Table 2.2). It can generate ensemble outputs from uncertain parameter input ranges.

Table 2.2. Components of the GWv3 Modified Pitman model (Adapted from Tanner, 2013)

Parameter	Units	Parameter description
Surface water parameters		
RDF	-	Rainfall distribution factor. Controls the distribution of total monthly rainfall over four model iterations
AI	fraction	Impervious fraction of catchment
PI1s	mm	Summer Interception storage for vegetation type 1
PI1w	mm	Winter Interception storage for vegetation type 1
PI2s	mm	Summer Interception storage for vegetation type 2
PI2w	mm	Winter Interception storage for vegetation type 2
AFOR	%	% area of catchment under vegetation type 2
FF	-	Ratio of potential evaporation rate for Veg2 relative to Veg1
PEVAP	mm	Annual basin potential evaporation
ZMINs	mm month ⁻¹	Summer Minimum basin absorption rate
ZMINw	mm month ⁻¹	Winter Minimum basin absorption rate
ZAVE	mm month ⁻¹	Mode of distribution of absorption rate
ZMAX	mm month ⁻¹	Maximum basin absorption rate
ST	mm month ⁻¹	Maximum moisture storage capacity
SL	mm month ⁻¹	Soil moisture below which there is no recharge
POW	-	Power of the moisture storage runoff equation
FT	mm month ⁻¹	Runoff from moisture storage at full capacity
R	-	Evaporation-moisture storage relationship parameter
TL	months	Lag of surface runoff
Groundwater parameters		
GW	mm month ⁻¹	Maximum recharge depth at maximum moisture capacity
TLGMax	mm month ⁻¹	Maximum channel loss
GPOW	-	Power of the moisture storage recharge equation
DD	km km ⁻²	Effective drainage density for groundwater inputs to streamflow
T	m ² day ⁻¹	Groundwater transmissivity
S	-	Groundwater storativity
RG	-	Initial groundwater drainage slope
Rest RWL	m (below surface)	Rest Water Level; aquifer depth
RSF	%	Riparian Strip Factor. Controls riparian evaporation losses from groundwater storage
GW Abstraction U&L	Mly ⁻¹	Groundwater abstraction from Upper and Lower slopes

2.6.3 Groundwater recharge estimation in the Modified Pitman Model

The modified Pitman model contains four key parameters that affect groundwater recharge volume (Tanner, 2013). These parameters are ST, SL, GW, and GPOW (full description can be found in Table 2.2). The model calculates recharge using a non-linear function of the soil storage and a maximum monthly recharge parameter as shown in Equation 2.1. To note here is

that there can be recharge into the aquifer from the river channel if the gradient is negative (water moves from the river to groundwater store) and discharge if the gradient is positive (water moves from the groundwater store to the river) (Hughes, 2004; Tanner, 2013; Tumbo et al., 2015). This is how the Pitman model can estimate recharge while considering SW-GW interactions.

$$RE = GW \frac{(S-SL)^{GPOW}}{(ST-SL)} \quad \text{Equation 2.1}$$

Where RE refers to recharge rate on monthly scale in (mm), GW is maximum recharge depth at maximum moisture capacity (mm month⁻¹), S is current soil moisture storage level (mm), SL is soil moisture below which there is no recharge (mm month⁻¹), $GPOW$ is the power of the moisture storage recharge which is usually expected to reflect similar physical relationships such as POW and ST represent maximum moisture storage capacity (mm month⁻¹).

2.7 The SWAT model

According to Rossetto et al (2019), Soil Water and Assessment Tool (SWAT) is a public domain, physically based and lumped code model, developed to simulate several different physical processes (hydrology, erosion and sediment yield, crop growth and nutrient cycling). Arnold et al. (2012), stated that SWAT is a data-intensive tool, thus, usually makes beginner model users stunned by the magnitude of the number of required inputs.

Nevertheless, as of now (40 years), it has been gaining international recognition and acceptance as one of the robust interdisciplinary watershed modelling tools (Bera et al., 2021; Sao et al., 2020; Senent-Aparicio et al., 2017). The recognition is evidenced by international SWAT model conferences and scientific publications where a great deal of SWAT model-related papers is presented and published in peer-reviewed journals each year (Obiero et al., 2020; Oeurng, 2018; Krysanova and White, 2015).

According to an online search done by running literature list of SWAT papers kept on SWAT's website by the current researcher on 2nd August 2022, a total of 5182 published studies were found to have used the SWAT model over the past 22 years (2000-2022) worldwide. Akoko et al., 2021; Obiero et al., 2020 and Rossetto et al., 2019 also demonstrated the increase in the application of the SWAT model on the African continent, (Figure 2.6), with recent literature database maintained on the SWAT model website (accessed on 2nd August 2022 by current

researcher) indicating about 140 published scientific papers applied SWAT in Africa from 2000 to 2022.

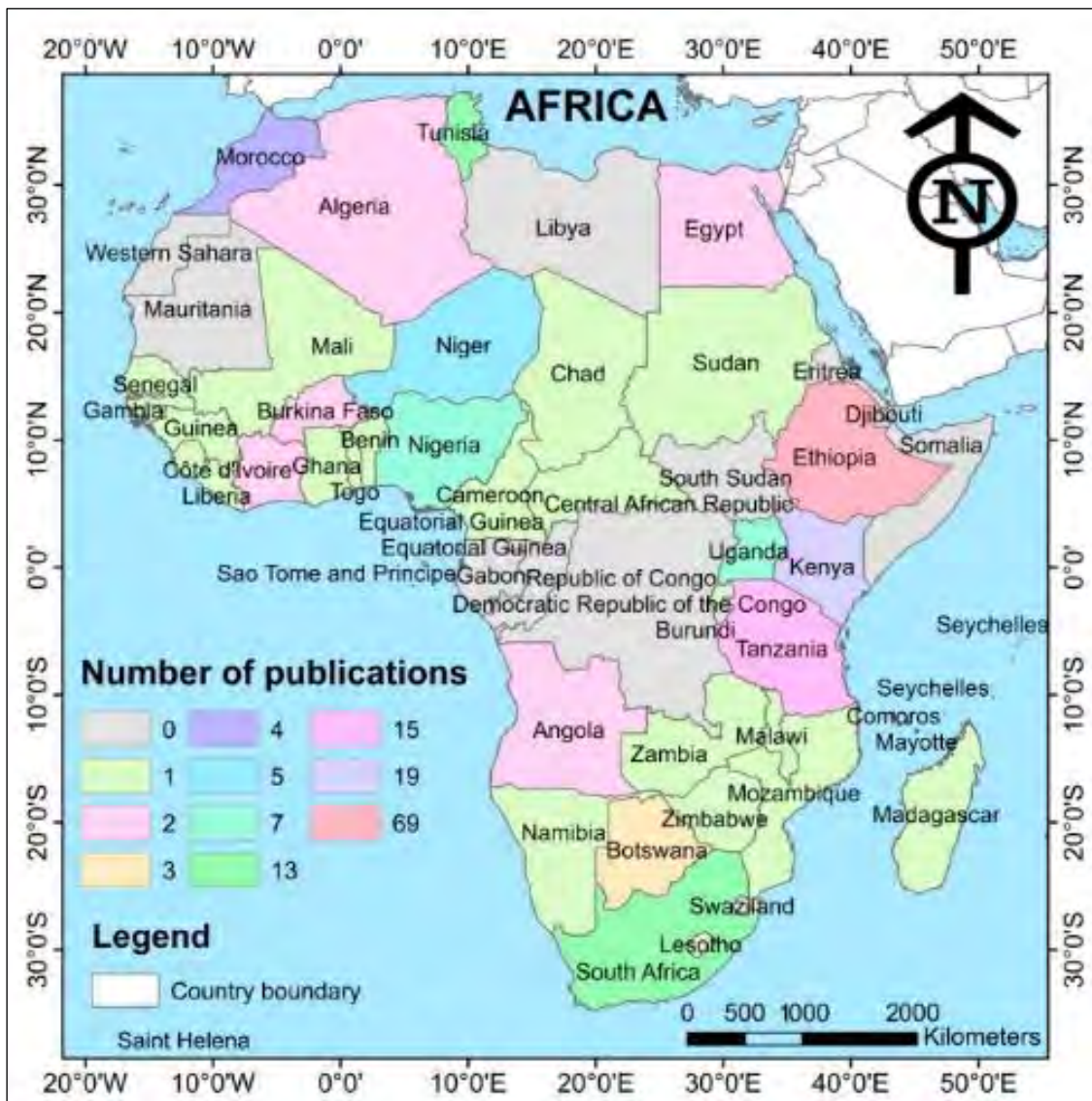


Figure 2.6. Application areas for SWAT model in Africa (Source: Akoko et al., 2021)

2.7.1 Model overview and structure

The model is open source and can run through Geographical Information System (GIS) interfaces, using either ArcGIS (ESRI) or QGIS platforms, which have demonstrated attractive features for users and enhance their functionality (Koltsida et al., 2021; Krysanova and White, 2015; Rossetto et al., 2019), also one can build the model outside GIS platforms. During the past two decades, SWAT has passed through repetitive reviews, testing, modifications, and enhancements which have led to the development of different versions with several of these

versions still available on the SWAT website (Arnold et al., 2012; Koltzida et al., 2021; Krysanova and White, 2015; Rossetto et al., 2019; Srinivasan, 2009).

SWAT2012 is the current major version of the SWAT model that can be set-up and run via ArcGIS software (Gelebo et al., 2022), using ArcMap 10.0 version and above, being distributed and hosted on (<http://swat.tamu.edu/>). The current study adopted the version since SWAT model is physically based, it makes use of spatio-temporal input datasets such as topography (DEM), land cover, and soil (Figure 2.7) to discretize an area under study into various internally homogeneous units, called hydrological response units (HRUs), which approximate the system’s behaviour and where all the budget terms are computed at their outlets within sub-basins (Rossetto et al., 2019).

Surface and vadose zone processes are calculated for each HRU with their outflows then being aggregated to their respective sub-basin (Rossetto et al., 2019). Groundwater storage and outflow is calculated at the sub-basin scale. (Krysanova and White, 2015; Senent-Aparicio et al., 2017).

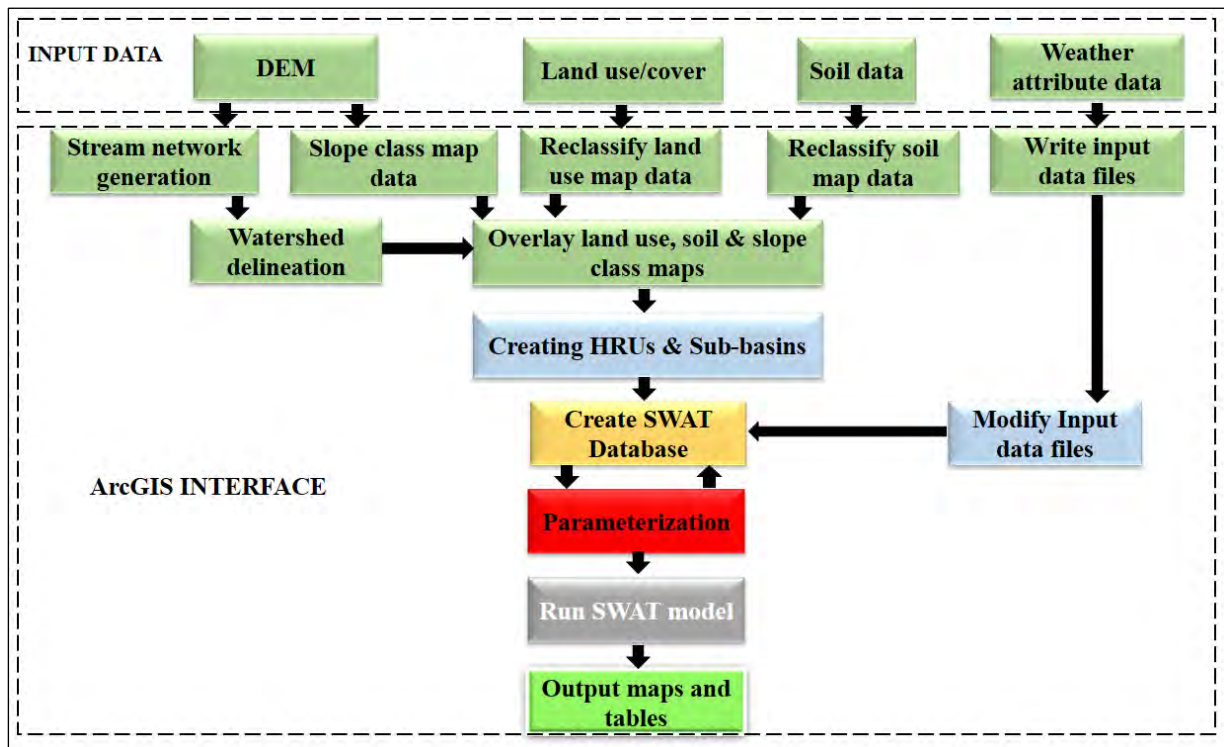


Figure 2.7. Conceptual structure of the SWAT model

2.7.2 Groundwater recharge estimation in the SWAT Model

SWAT model has few physical and empirical algorithms that are used to estimate groundwater recharge depending on the process. A water balance is calculated for each HRU in the model, which includes percolation out of the bottom of the soil profile which recharge the sub-basin aquifers below (Abbaspour et al., 2007; Arnold et al., 2000; Rossetto et al., 2019). Percolation out of the soil profile is calculated based on soil moisture in the bottom layer of the soil, the conductivity of the soil, and assumed depth to impervious.

After calculating the amount of water that percolates out of the bottom layer of the soil profile (W_{seep}), SWAT applies a lagging function in routing the water to the aquifers below, to represent percolation through a vadose zone between the soil and the water table (Rossetto et al., 2019). It is then lagged to the aquifers based on parameterisation of an intermediate vadose zone (Arnold et al., 2012). In the current study, to estimate groundwater recharge, the HRU water balance approach was used to estimate the amount of water that percolates (W_{seep}) through the soil to feed groundwater aquifers using Equations (2.2 to 2.5).

$$R - E - Q_{hru} - W_{seep} - dS_{soil} = 0 \quad (\text{Equation 2.2})$$

$$Q_{hru} = Q_{surface} + Q_{lateral} \quad (\text{Equation 2.3})$$

$$dS_{soil} = SW_t - SW_o \quad (\text{Equation 2.4})$$

$$dS_{soil} = Infiltration - E - Q_{lateral} - W_{seep} \quad (\text{Equation 2.5})$$

Where SW_t refers to final soil water content, SW_o represents initial soil water, R refers to precipitation, $Q_{surface}$ represents surface runoff, Q_{hru} represent amount flow in hydrological response units, dS_{soil} change in soil moisture store, E represents evapotranspiration, W_{seep} is the percolation and $Q_{lateral}$ relates to amount of lateral flow (all in mm).

The model can allocate the calculated (using an exponential decay function) recharge between both a shallow and deep aquifer at every HRU and its respective sub-basin representing the delay time of recharge due to geologic formations (Arnold et al., 2012, 2000; Moriasi et al., 2012; Rossetto et al., 2019). Rossetto et al (2019) stated that groundwater discharge from the shallow aquifer to surface streams within the SWAT model is estimated depending on empirical parameter and the base flow recession constant. Dekongmen et al (2022), stated that, “a shallow aquifer in SWAT is one whose depth ranges from 2 to 20 m while a deep aquifer is

one whose depth is above 20 m” (Figure 2.8). Equation 2.6 and Equation 2.7 can be used to estimate the recharge volume partitioning between the shallow and deep aquifers.

$$W_{rch.sh} = W_{rchg} - D_{p_rech} \quad (\text{Equation 2.6})$$

$$D_{p_rech} = \beta_{deep} * W_{rchg} \quad (\text{Equation 2.7})$$

Where $W_{rch.sh}$ is the amount of recharge entering shallow aquifer per day_i (mm), D_{p_rech} represents recharge volume entering the deep aquifer per day_i (mm) and β_{deep} refers to percolation coefficient of the aquifer.

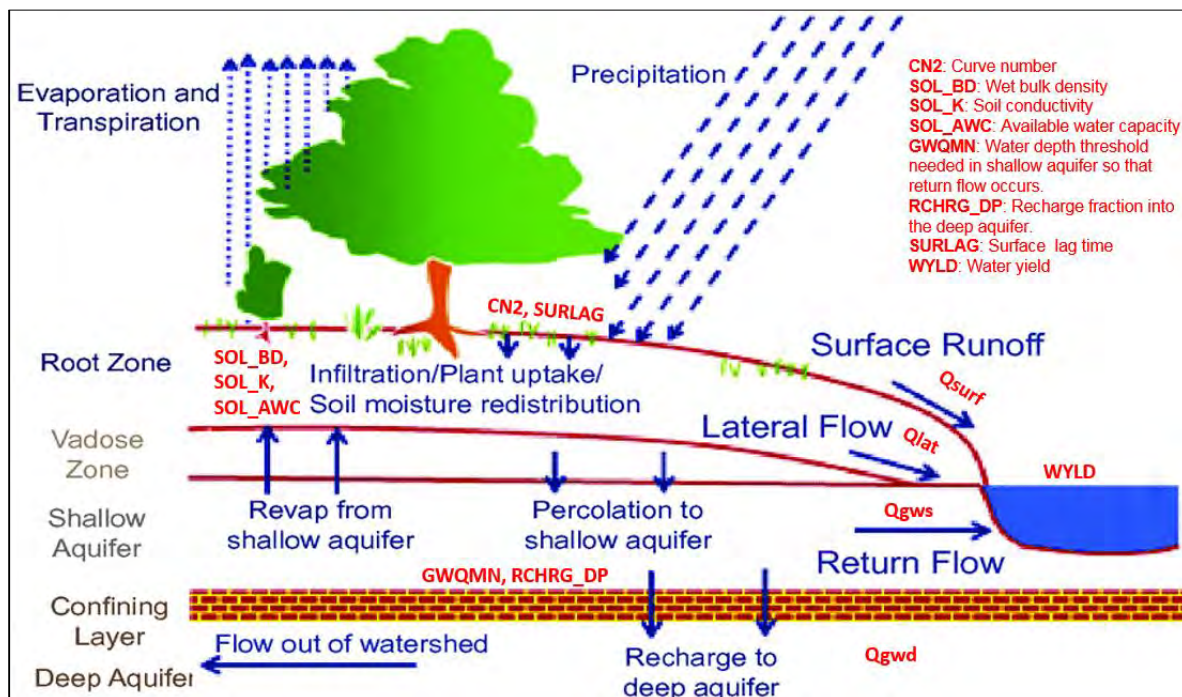


Figure 2.8. Hydrological modules in SWAT model with associated processes (Adapted from Neitsch et al., 2005)

2.8. Groundwater recharge model processes in SWAT and Pitman models

SWAT model has got few physical and empirical algorithms that are used to estimate groundwater recharge depending on the process (Abbaspour et al., 2007; Arnold et al., 2000; Rossetto et al., 2019), however, the model can allocate the calculated groundwater recharge (using an exponential decay function) between both a shallow and deep aquifer at every HRU and its respective sub-basin (Arnold et al., 2012; Moriasi et al., 2012; Rossetto et al., 2019). Additionally, since the model is a physically based, semi-distributed model, and its inputs have

a spatial-temporal component, it has the capability of predicting the effects of climate change on water balance and, eventually, groundwater recharge (Awan et al.,2014, 2013).

The modified Pitman model contains four key parameters that affect groundwater recharge volume (Hughes et al., 2006; Tanner, 2013) and groundwater recharge is usually calculated using a non-linear function of the soil storage and a maximum monthly recharge parameter. Since the modified Pitman is purely a rainfall-run off conceptual model, it allows all the sub-basins in the model to be modelled with independent parameter sets (Kapangaziwiri, 2008).

Groundwater recharge is majorly estimated by considering the surface-groundwater interactions, for example, where water moves from the river to groundwater store (negative gradient) and from the groundwater store to the river (positive gradient) (Hughes, 2004; Sawunyama,2008; Tanner, 2013; Tumbo et al.,2015). It should be noted that within the Pitman model, climate change impacts on groundwater recharge are not directly predicted since the model only depends on rainfall, yet the spatial and temporal distribution of other parameters as the case in SWAT has a great deal of the impact on water resources presence and distribution (Awan et al., 2014; Tumbo et al., 2015).

CHAPTER THREE

STUDY AREA

3.1 Background

The upstream area supports the existence of one of South Africa's largest and most important artesian basins (1958 Km²), supplying approximately 1400 million litres per year of water to large agricultural irrigation schemes and domestic and industrial users within the Uitenhage area (Baron, 2000; Maclear, 2001; Nyawo, 2017). According to Parsons (2004), groundwater from the basin has been over-utilized for a long period of time which prompted the authorities within the basin to limit abstraction to sustainable rates by developing a groundwater control area.

3.2 Physiography and hydrology of the upstream area

According to Bailey and Pitman (2016), the upstream, falls within primary catchment "M" and comprises parts of three quaternary catchments (i.e., M10A, M10B, and half of M10C) with an area of about 859 Km² (approximately 45% of the total area of UAB) (Figure 3.1). The upstream area is dominated by steep sloped mountainous terrain, with multiple undulating features along the Kwa-Zungu, Elands, and Swartkops rivers that run from the north-western end to the south-eastern part.

The area embraces significant elevation band differences with the mean elevation values ranging from 1102m to 442m reducing downwards towards the downstream area of UAB (Figure 3.1). The upstream area envelopes the north-western Kwa-Zungu and western Elands Rivers as the two main tributaries and includes other smaller tributaries draining into the downstream part following a structural weakness of upstream zone (Maclear, 2001) (Figure 3.1). Additionally, there are Groendal and Bulk River dams, which supply water for irrigation and municipal services during dry events (Nyawo, 2017).

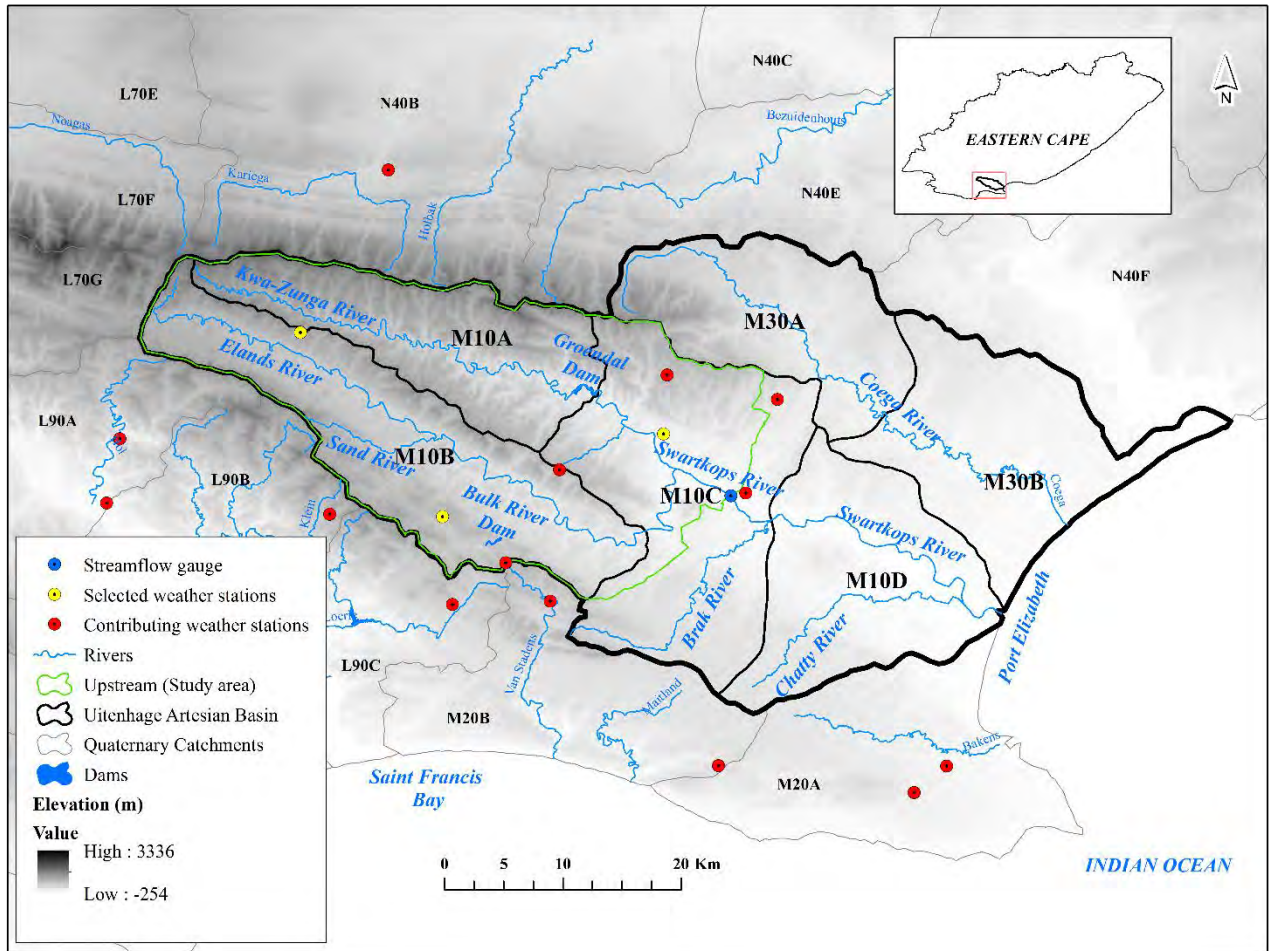


Figure 3.1. Map drawn in ArcGIS showing quaternary catchments of upstream area with respect to UAB, stream gauge, dams, contributing weather stations and showing elevation distribution

3.3 Climatology of the upstream area

The upstream area experiences semi-arid climatic conditions according to van Wyk (2010) and it is recharged by rainfall (550-770mm), with relatively more rain occurring in the highland ranges (Figure 3.2). These ranges, together with the apparent movement of the rain belt, Inter-Tropical Convergence Zone (ITCZ), coupled with prevailing winds from the Indian Ocean, provide fertile ground for the orographic and cyclonic seasonal rainfall variation shifts in the area (Figure 3.3). The area has moderate summers and mild winters with winds blowing from the southeast during summer and southwest during wintertime (Figure 3.3), and (Baron, 2000; Maclear, 2001, 1996). According to Bailey and Pitman, (2016), the estimated regional mean potential evaporation values in quaternary catchments of the upstream area (i.e., M10A, M10B, and M10C), are 1600, 1600, and 1550 mm respectively.

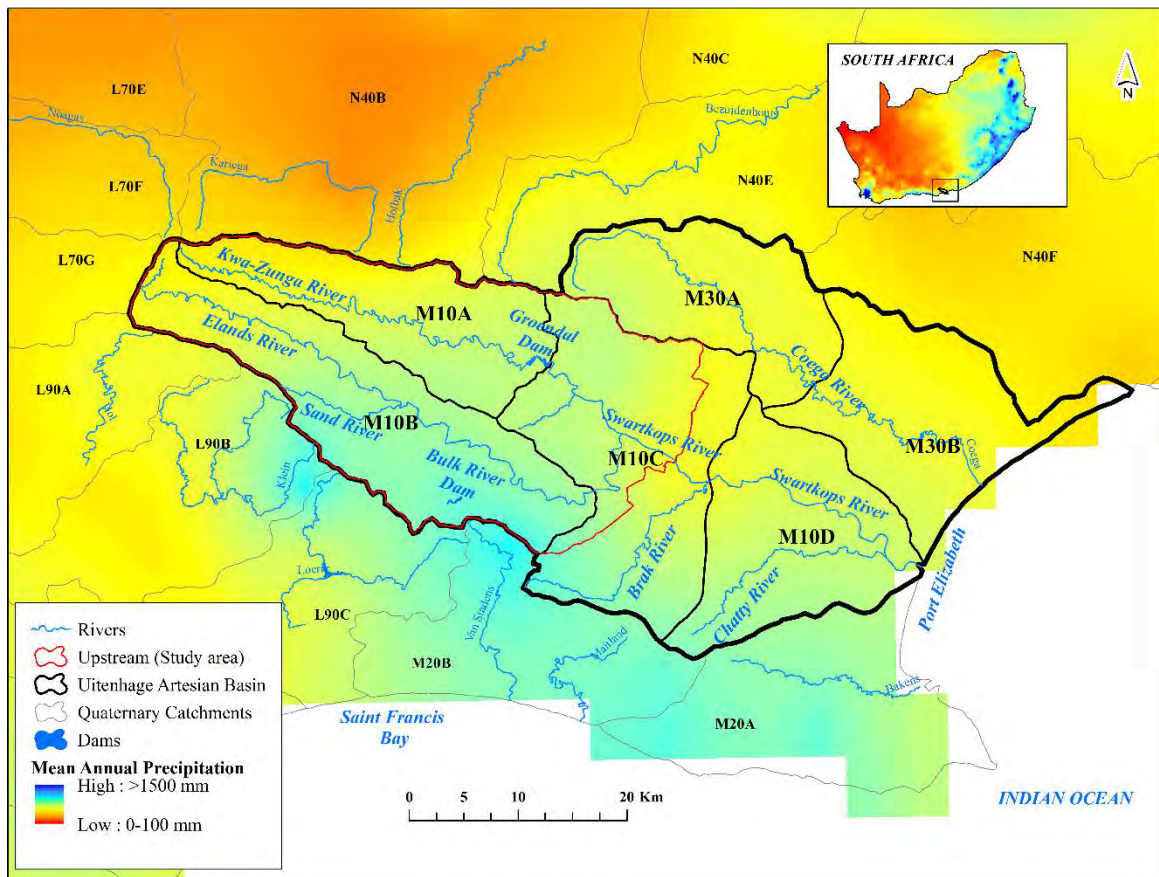


Figure 3.2. Map drawn in ArcGIS showing mean annual precipitation distribution within the study area (Source: WR2012 MAP)

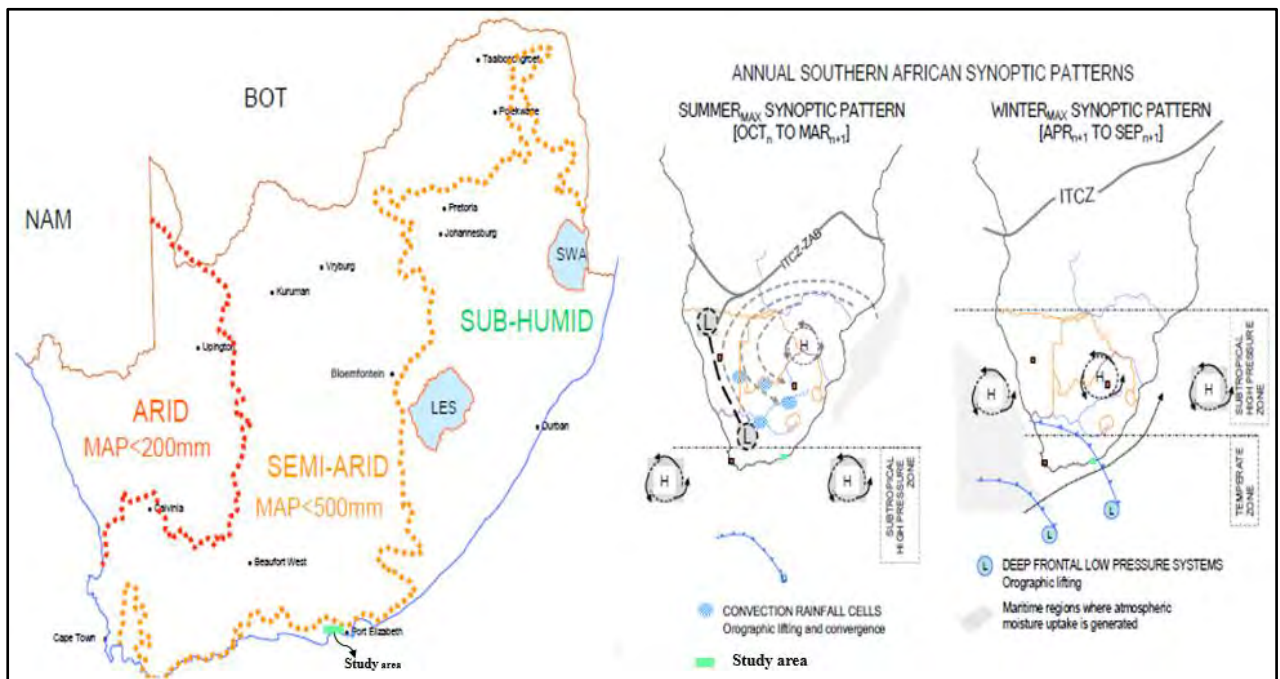


Figure 3.3. Climatic zones in Southern Africa and Synoptic seasonal migration of prominent weather systems during summer and winter periods (Adapted from van Wyk (2010))

3.4 Geology, landform, and soils of the upstream area

The central-western section of the upstream area (Figure 3.4 and 3.5), that forms the Elands catchment is underlined with the Bokkeveld shales, while the lower section of the upstream area falls under Uitenhage Group (UG), consisting of siltstones, mudstones, and claystones with patches of alluvium within the flood plains (Chabangu et al., 2014; Maclear, 2001). The fractured Table Mountain Group (TMG) sandstones with patchy rock outcrops (see Figure 3.4 and 3.5), cover almost the entire upstream area and are confined downslope by overlying cretaceous siltstones and mudstones, which are responsible for the artesian conditions in the downstream area (Chabangu et al., 2014; Maclear, 2001; Nyawo, 2017).

Furthermore, the upstream area embraces several structural fault systems (e.g., subsurface, surface, and thrust). However, in this area, the Coega Fault (with patches of subsurface and surface) (Figure 3.5), is the major structural feature that starts from the upstream area and goes downwards towards the Indian Ocean (Baron, 2000; Maclear, 2001).

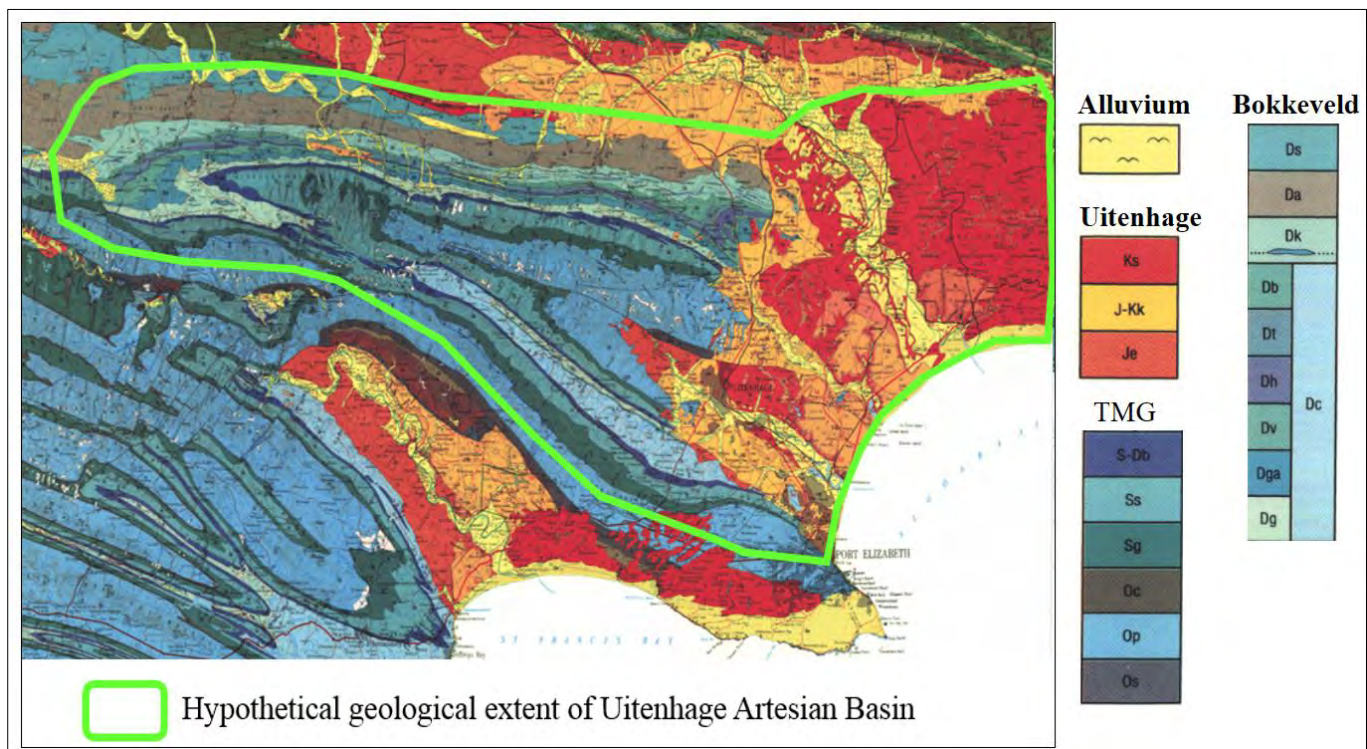


Figure 3.4. Geological location of the UAB within geology and topographical map sheet (Source: Council for Geoscience, South Africa)

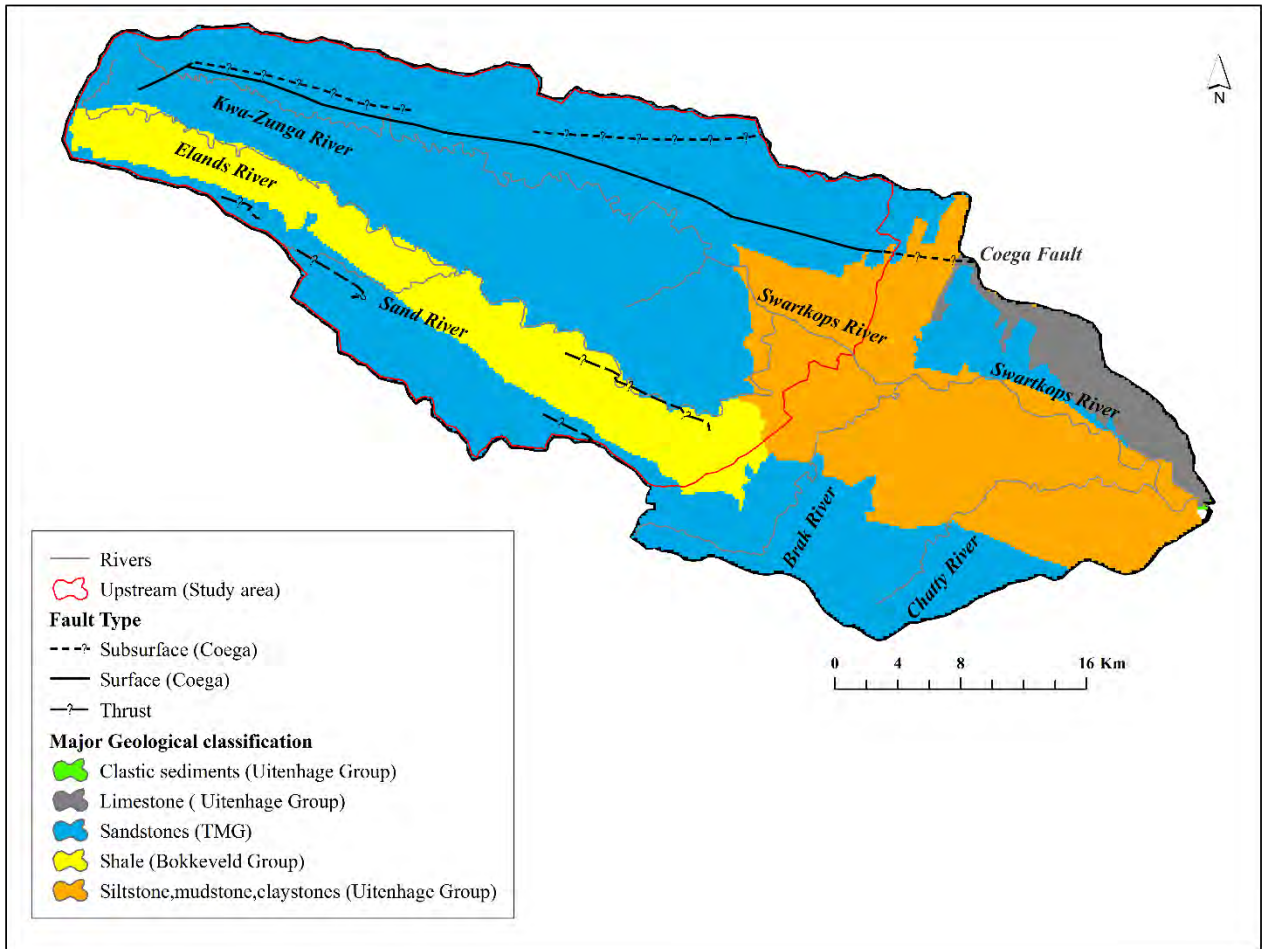


Figure 3.5. Map drawn in ArcGIS showing major geological classification (Source: SOTERSAF Database for Southern Africa)

In terms of the distribution of landforms (modified from SOTERSAF Database for Southern Africa), the upstream area is dominated by high-gradient mountain areas (see Figure 3.6), followed by medium-gradient hills with patches of plain and valley floor landforms dominating the lower section of upstream. The distribution of these landforms provides fertile ground for the generation of both local and regional groundwater recharge since they provide efficient mechanism for water to bypass the soil matrix through a network of preferential channels when the system is in a wet state (Maclear, 2001; Savenije and Hrachowitz, 2017; Savenije, 2010).

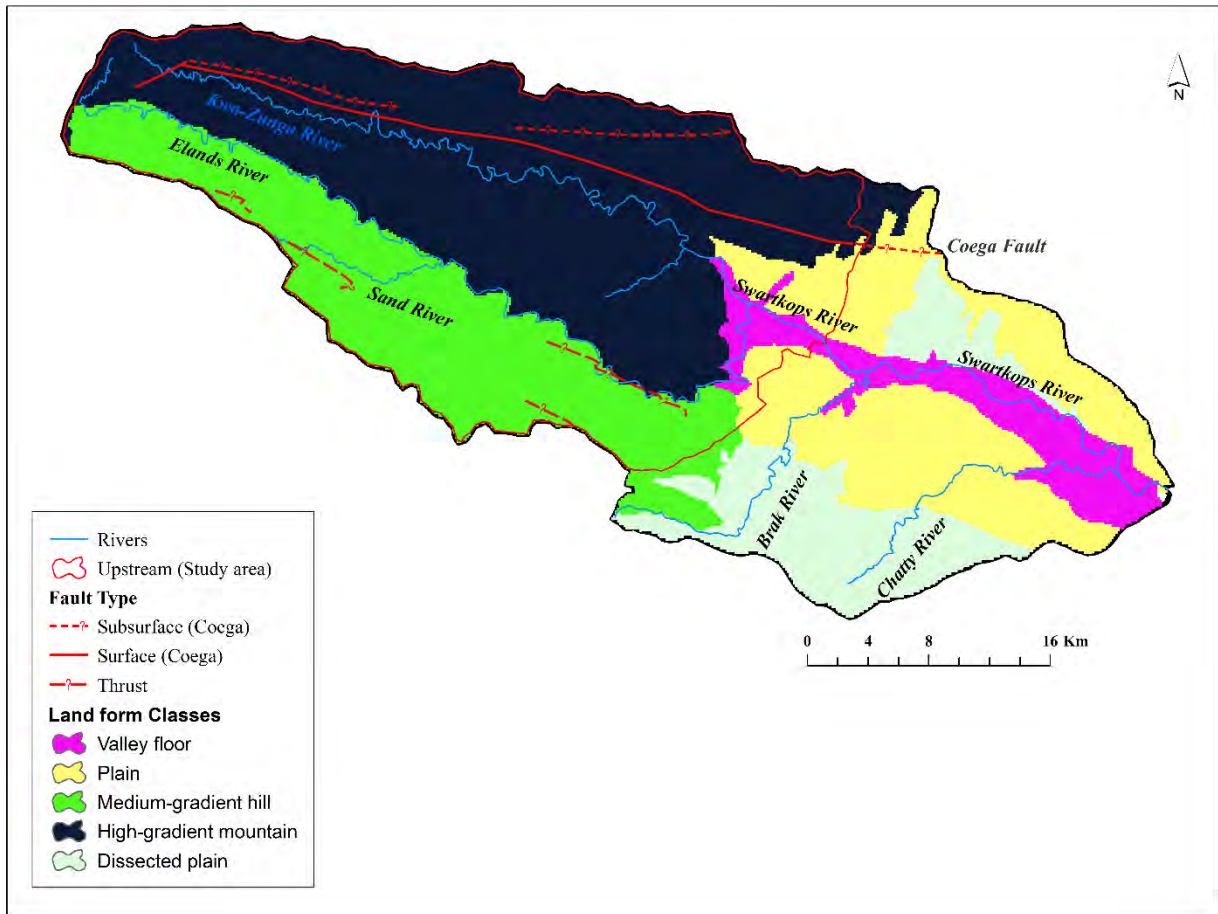


Figure 3.6. Map drawn in ArcGIS showing landform classification (Source: SOTERSAF Database for Southern Africa)

The digital soil map (modified from SOTERSAF Database) shows the various several soil classes within the upstream area which are assumed to have an impact on groundwater recharge generation. From (Figure 3.7), Lithic Leptosols (Clay-Loam, very thin soils over continuous rock with extremely rich in coarse fragments; 48.2%) dominate the upstream area, Calcic Luvisols (substantial accumulation of carbonates; 18.2%), Eutric Regosols (Sandy-Loam, very weakly developed mineral soils in unconsolidated materials without a horizon common in extensively eroding areas; 13.2%), Gleyic Planosols (slowly permeable subsoil with more clay content; 9.0%) Chromic Luvisols (Clay-Loam, have higher clay content in the subsoil than in the topsoil; 7.2%), Epipetric Calcisols (carbonate content; 3.6%), Arenic Regosols (deep sandy soils; 0.5%) and least being Albic Arenosols (0.1%).

These different soil classes together with other factors influence the rate of rainwater infiltration and percolation where those with high sand and silt content (Lithic Leptosols, Eutric

Regosols and Arenic Regosols) highly facilitate recharge compared with those with higher clay content (Chromic Luvisols and Gleyic Planosols).

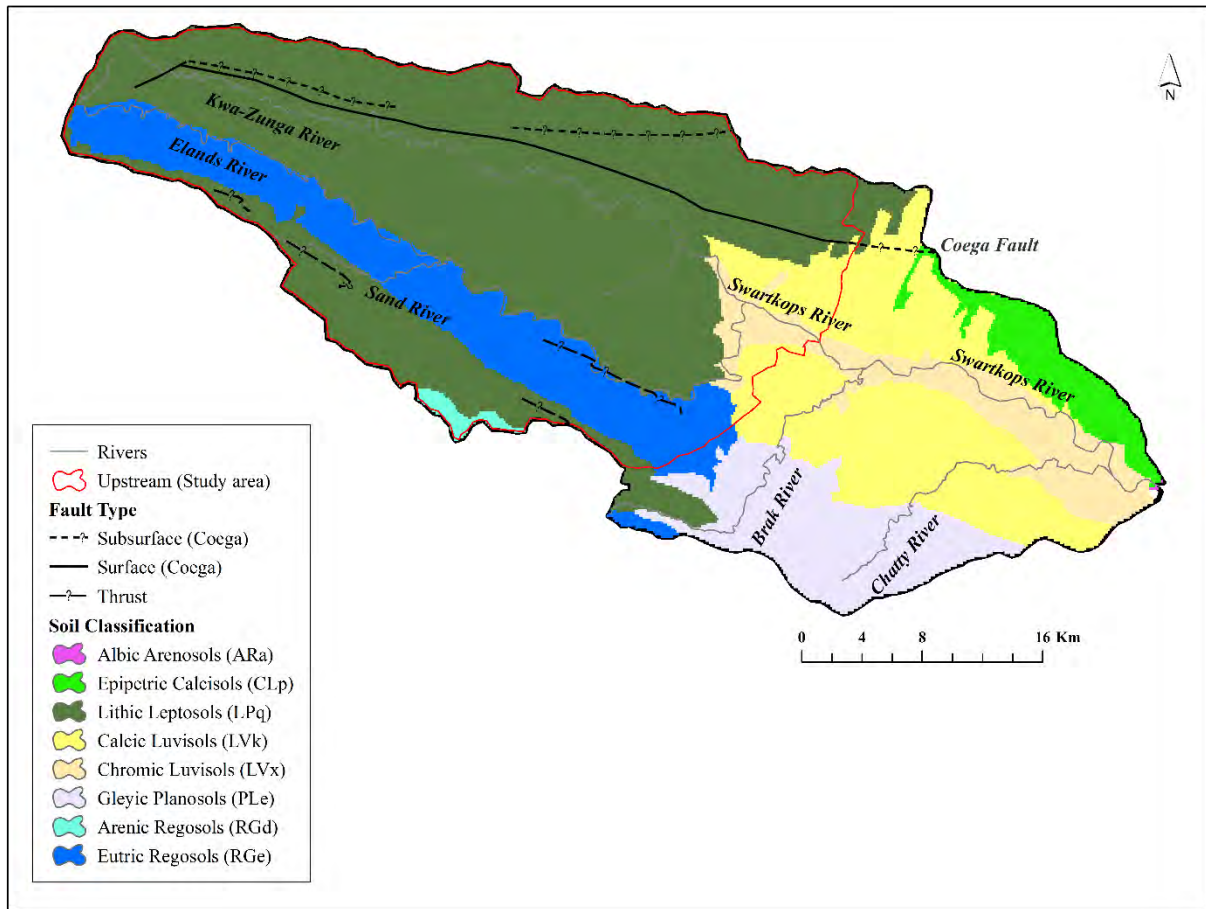


Figure 3.7. Map drawn in ArcGIS showing soil classification (Source: SOTERSAF Database for Southern Africa)

3.5 Land use/cover

Figure 3.8 shows the land cover distributions within upstream area which are presumed to influence groundwater recharge dynamics. The area is covered with shrub land (28.7%), forested land (28.0%) with patches of grassland (10.7%; low fynbos), and wetlands (2.8%). Agricultural activities (8.9%) mostly by irrigation (Maclear, 2001) are mainly found in the western part of the Elands River valley and the downstream area near Uitenhage Town. Built up area (17.0%) is majorly concentrated in the Uitenhage Town at the extreme downstream with few patches in the upper section. Also, the area has some reservoirs, Groendal dam, Bulk River dam, and river systems (2.5%), which offer water needed by farmers for irrigation purposes (Maclear, 2001; Nyawo, 2017). In addition, there are some patches of barren land, sand mining, salt mining and mineral quarries (1.5%).

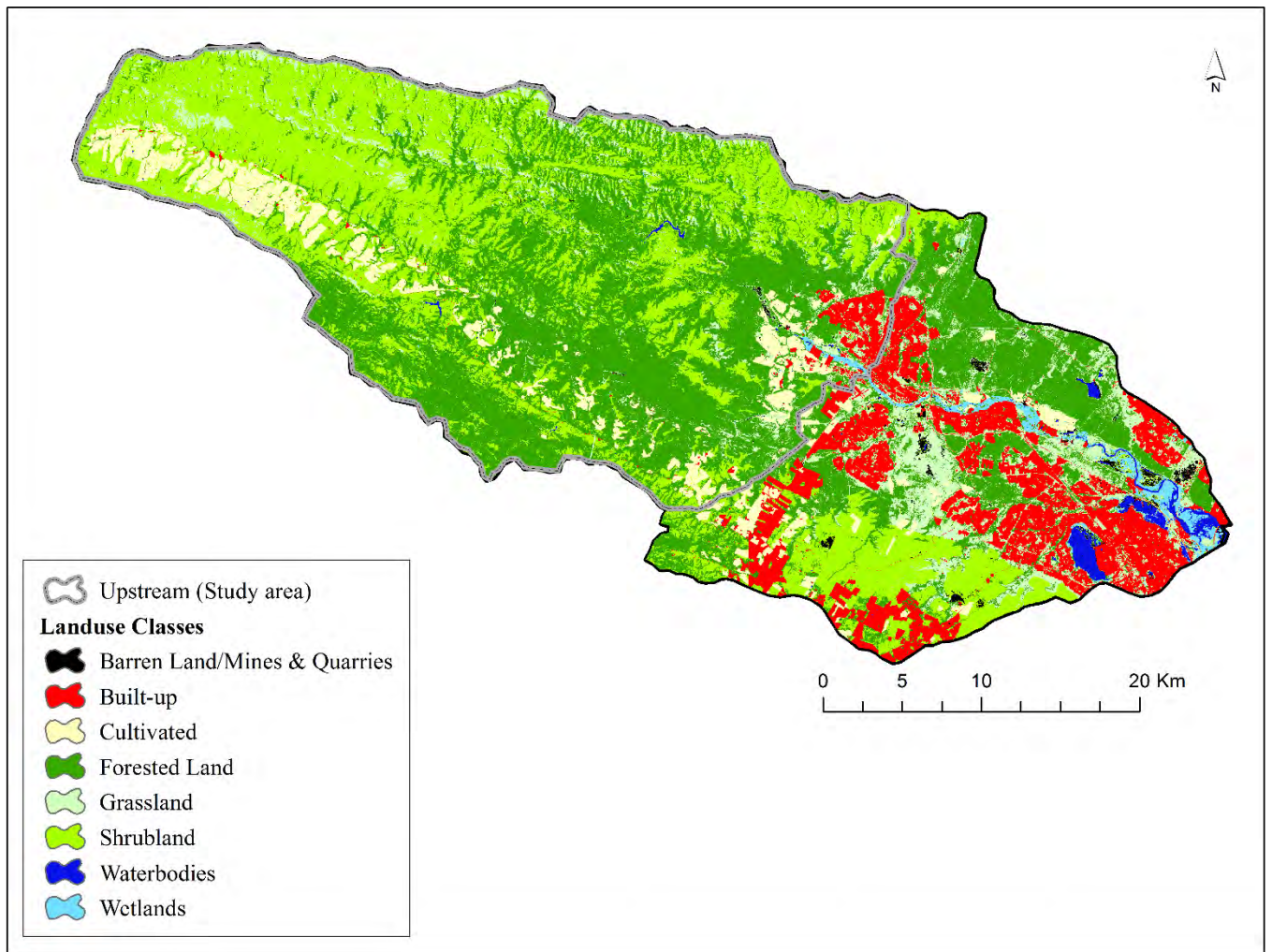


Figure 3.8. Map drawn in ArcGIS showing land use/cover classification (Source: South African National Land-Cover).

CHAPTER FOUR

METHODOLOGY

4.1 Data and its Sources

In the current study, a variety of datasets were utilized including climate, soil, DEM, hydrological datasets, land cover, and others from published studies in UAB. Details of these datasets are described within the subsections below.

4.1.1 Climate/weather data

Daily precipitation, temperature, wind speed and relative humidity for a period of 31 years (1993 to 2021) were obtained from sources such as South Africa Weather Services (SAWS) [www.weathersa.co.za/] and Water Resources Simulation Model 2012 (WR2012) database (waterresourceswr2012.co.za) (Bailey and Pitman, 2016; Pegram et al., 2016). A study by (Hughes, 2019b) suggested that large areas within the African continent lack enough monitoring points to provide hydro-climate-related datasets, thus creating frequent data gap problems.

The upstream area is not immune from the mentioned problems and thus, other climate dataset sources such as Water Productivity through Open access of Remotely sensed derived data (WaPOR) [https://wapor.apps.fao.org/home/WaPOR_2/1] (FAO, 2018) specifically for daily precipitation, Climate Forecast System Reanalysis (CFSR) [<https://swat.tamu.edu/data/cfsr>] (Dile and Srinivasan, 2014; Fuka et al., 2014), for temperatures, wind and relative humidity, were applied to compliment station data from SAWS and WRC database. Station data obtained from SAWS was for Bulk River and Uitenhage weather stations and included (Rainfall, maximum and minimum temperatures, wind, and relative humidity) with missing years (1995-1998).

The missing data was filled using point location data from WaPOR and CFSR. No weather station is in the upper most part of the upstream area, consequently, a dummy weather station (Table 4.1) was created. Using the Inverse Distance Weighting technique (IDW), (Chen and Liu, 2012) (Equations 4.1 and 4.2), rainfall estimates for this station were created while using Bulk River and Uitenhage stations together with contributing neighboring weather stations available from WR2012 database (see Figure 3.1).

Other weather parameters (maximum and minimum temperatures, wind, and relative humidity) for the Dummy station were obtained from CFSR website. It should be noted that in all the

three stations (Table 4.1), data for solar radiation was not available and it was thus assumed to be spatially uniformly distributed throughout the upstream area and as a consequence, it was automatically generated within the SWAT model considering the representation of the Southern hemisphere (Abbaspour, 2015; Laura, 2010).

Furthermore, in the current study, three weather stations were chosen based on their relative position within the quaternary catchments with a view to at least represent spatial weather distribution across the three quaternary catchments (M10A, M10B and M10C; see Figure 3.1).

$$\check{R}_p = \sum_{i=1}^N w_i R_i \quad (\text{Equation 4.1})$$

$$w_i = \frac{d_i^{-\alpha}}{\sum_{i=1}^N d_i^{-\alpha}} \quad (\text{Equation 4.2})$$

Where \check{R}_p is the unknown rainfall data (mm), R_i represents data for rainfall from known weather stations (mm), N refer to number of weather stations, w_i represents weighting for individual weather station, d_i represents distance from individual weather station to the unknown point and α refers to power and control parameter between the two points in consideration (Chen and Liu, 2012).

Table 4.1 Chosen weather stations

ID	Name	Longitude	Latitude	Elevation (m)
1	Dummy	24.997	-33.642	879
2	Bulk River	25.123	-33.784	544
3	Uitenhage	25.326	-33.724	442

4.1.2 Hydrological data sets

Daily streamflow datasets with a period of 28 years (1993-2021) were obtained from the Department of Water and Sanitation (DWS) [www.dws.gov.za/] using stream gauge located on Swartkops River (M1H012) at Uitenhage area (see Table 4.2). Catchment boundary datasets in form of shapefiles at a quaternary level were sourced from the Department of Water and Sanitation (DWS) database of South Africa Water Research Commission. There were no field measurements to get current information on boreholes therefore, the current study relied on published borehole information that was used by Maclear (2001) in UAB.

This information included datasets on groundwater levels, borehole depth and aquifer hydraulic properties such as yield and geology (Table 4.3). The study also made use of Hydrogeological Map

series for a country-wide extent of aquifer type (amalgamation scale of 1:500000), Average Groundwater Exploitation Potential [AGEP], and information from Groundwater Resource Assessment Phase II, and Water Research Commission (WR2012) (Figure 4.1).

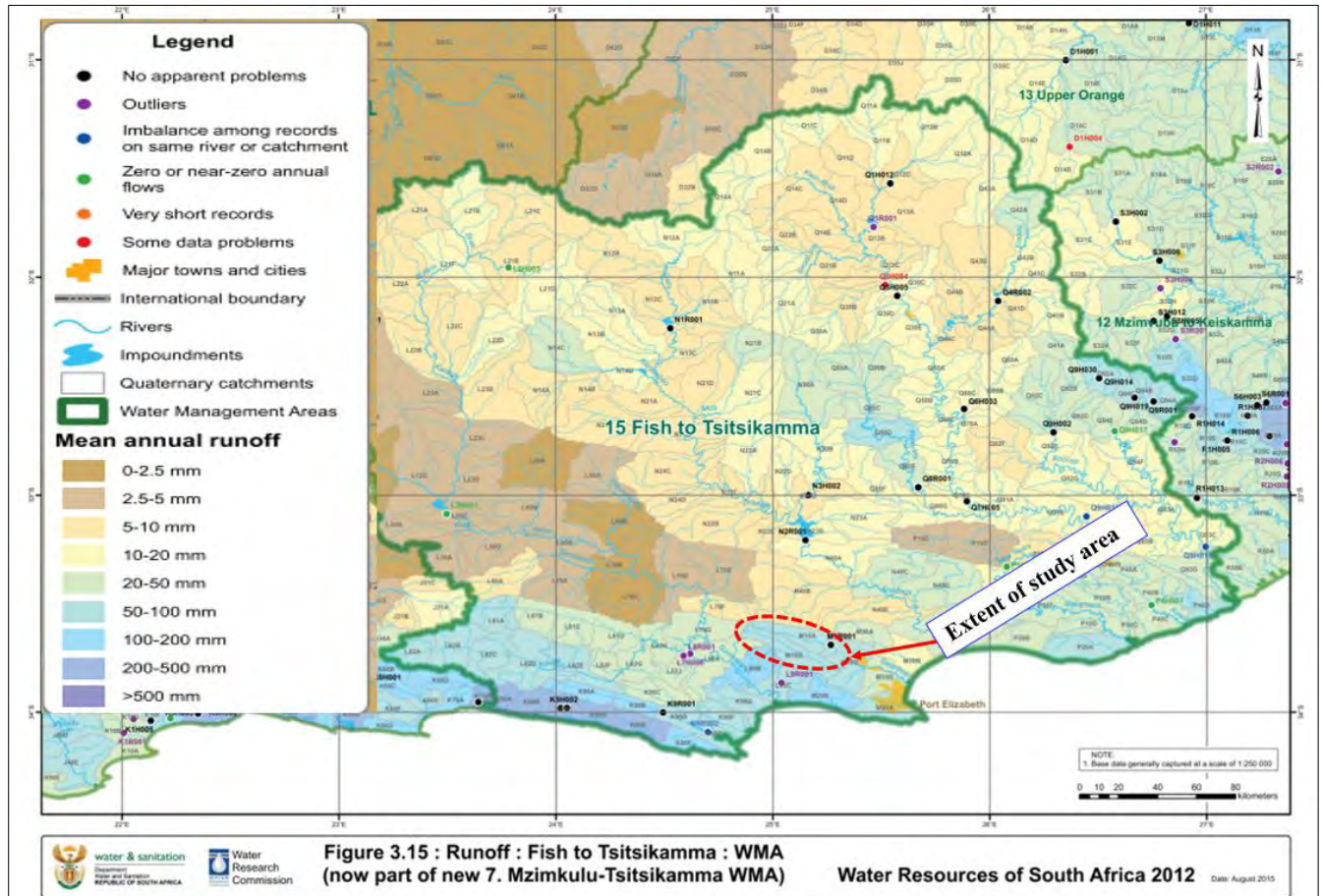


Figure 4.1. Map showing mean annual regional runoff (Adapted from Bailey and Pitman, 2016)

Table 4.2. Stream gauge station information (Source: Researcher)

ID	Name	Longitude	Latitude	Elevation (m)
M1H012	Swartkops River@Uitenhage	25.3863	-33.7719	420

It should be noted that the stream gauge is located downstream of the Groendal and Bulk River Dams (Figure 3.1), model set-ups did not aim to represent these dams as the required data details on them were not obtained.

Table 4.3. Sample of borehole and well information (Source: Maclear, 2001)

SITE_TYPE	Longitude	Latitude	Elev_mamsl	Water_use	Pump_type	Yield(l/s)	Geology	WL(mbs)	WL(mamsl)	BHDepth_m
BH	345028.86	6261655.86	66	I	S	11.4/12.9	mdsn+qrtz+snds	27.2	38.8	200
BH	345952.81	6263396.26	62	DSI	T	5.7	mdsn+snds	9	53	183
BH	345603.76	6261110.58	68	DSI	S	6.3/10.3	mdsn+snds	15	53	182
BH	345758.10	6261113.07	78	N	N	1	mdsn+snds	43.95	34.05	91.44
BH	348370.33	6263496.58	47	N	N	0	alvm+mdsn	3.47	43.53	4
BH	348681.03	6263378.27	45	N	N	0	alvm+mdsn	1.67	43.33	4
BH	348783.94	6263379.90	46	N	N	0	alvm+mdsn	1.12	44.88	3
BH	348910.15	6263535.95	45	N	N	0	alvm+mdsn	1.13	43.87	5
BH	349126.20	6262892.34	44	N	N	0	alvm+mdsn	1.83	42.17	6
BH	339756.37	6270719.98	198	N	N	0.3	qrtz+snds	1	198	240
BH	345358.78	6261938.52	64	DS If	S	9.5/11.4	mdsn+snds	27	37	>78
BH	347875.39	6262256.27	54.5	D	S	0.8	qrtz+snds	11.9	42.6	182
BH	345549.82	6261263.76	65	D Iv	S	8.8/6.5	alvm+mdsn+qrtz+snds	37	28	176
BH	347599.30	6261820.51	84	SI	S	1.3	qrtz+snds	38.8	45.2	152
BH	302171.15	6277012.78	573	DSI	N	1.0/2.0	snds	1	572.99	136
BH	301540.66	6275088.96	600	DSI	N	0.8	snds	1	599	168
BH	304892.14	6277592.42	552	DS	N	0.5	?	1	552	120
BH	344170.29	6259084.50	78	S	P	0.2/0.3	snds	11.77	66.23	50
BH	345329.80	6260551.53	67.5	DSI	M	10	snds	19	48.5	122
BH	345932.01	6258312.04	89	SBr	P	0.2/0.4	?	24	65	369
BH	345740.17	6262221.99	65	GD	M	21	mdsn+snds	30	35	73.2
BH	345741.66	6262129.58	67	GD	S	0.9	mdsn+shle+snds	25	42	132
BH	346218.53	6262876.75	70	N	N	2.5	mdsn	37.99	32.01	177
BH	346136.88	6263152.74	64	DS Iv	S	6.7	mdsn+snds	52.19	11.81	107
DW	342849.16	6254964.81	157	S	C	0.4	?	4.32	152.68	8.55
DW	344994.08	6265383.48	61	S1	C	?	alvm	1.8	59.2	5.13
DW	345387.57	6264927.69	55	DSI	C	?	alvm	1.7	53.3	4.68

Site; BH(Borehole), DW(Dug well):**Water use;** Br(brick manufacture),C(Chicken farm), D(Domestic), Da(Dairy farm),G(Garden), I(irrigation), If(Fruit), Il(Lucerne), Iv(Vegetable), N(None), S(Stock watering): **Pump type;** C(Centrifugal), M(Moon), P(Piston), S(Submersible),T(Turbine), N(Not known),W(Wind-pump): **Geology;** alvm(alluvium[silt, sand, river, gravel, boulders]), mdsn(mudstone), qrtz(quartzitic) , shle (Shale) and snds (sandstone[qrtz snds=TMS])

4.1.3 Catchment spatial input datasets

Datasets (Table 4.4) were extracted and processed in ArcMap10.2.2, software. Classification, identification, and scientific description of (lithology, soils, and land use) was done using the Soil and Terrain (SOTER) manual and Agricultural Research Council-South Africa (ARC) conventions together with GIS techniques. Lithology was classified into five classes, soils classified into eight, landform into five and land cover type into eight classes using reclassify tool, in ArcMap 10.2.2. (Figure 4.2 and Table 4.5).

Table 4.4. Catchment spatial data datasets

Data type	Extent	Format	Source
Lithology	Regional	Shapefile	Soil Terrain of Southern Africa (SOTERSAF) Database and ARC
Geology	Regional	Shapefile	Soil Terrain of Southern Africa (SOTERSAF) Database and ARC
Geological Top sheet	1:250000; Geological Series	Raster	3324 Port Elizabeth; Council of Geological Science-South Africa
Soils	Regional	Shapefile	Soil Terrain of Southern Africa (SOTERSAF) Database (Batjes, 2008; Dijkshoorn, 2003 and Senent-Aparicio et al., 2017) FAO Africa soils (https://library.mcmaster.ca/maps/geospatial/soil-and-terrain-database-southern-africa-sotersaf); [www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soildatabase-v12/en/] and ARC
Land use	Updated (2018-2020) Local	Raster	South African National Land-Cover (SANLC) database [www.dffe.gov.za/projectsprogrammes/egis_landcover_datasets] and ARC
DEM	30 m × 30 m	Raster	National Aeronautics and Space Administration (NASA)'s Shuttle Radar Topography Mission (NASA SRTM) (Farr et al., 2007) https://srtm.csi.cgiar.org/srtmdata/

Table 4.5. Lithology, soil, and landform classification

Parameter	Classification	Description
Lithology	SC	Clastic sediments
	SC2	Sandstones
	SC3	Siltstone, claystone
	SC4	Shale
	SO1	Limestone and other carbonates
Soil	CLp	Epipetric Calcisols
	LPq	Lithic Leptosols
	LVk	Calcic Luvisols
	LVx	Chromic Luvisols
	PLe	Gleyic Planosols
	RGd	Arenic Regosols
	RGe	Eutric Regosols
	ARa	Albic Arenosols
Landform/geomorphology	SP	Dissected plain
	TM	High-gradient Mountain
	SH	Medium-gradient hill
	LP	Plain
	LV	Valley floor

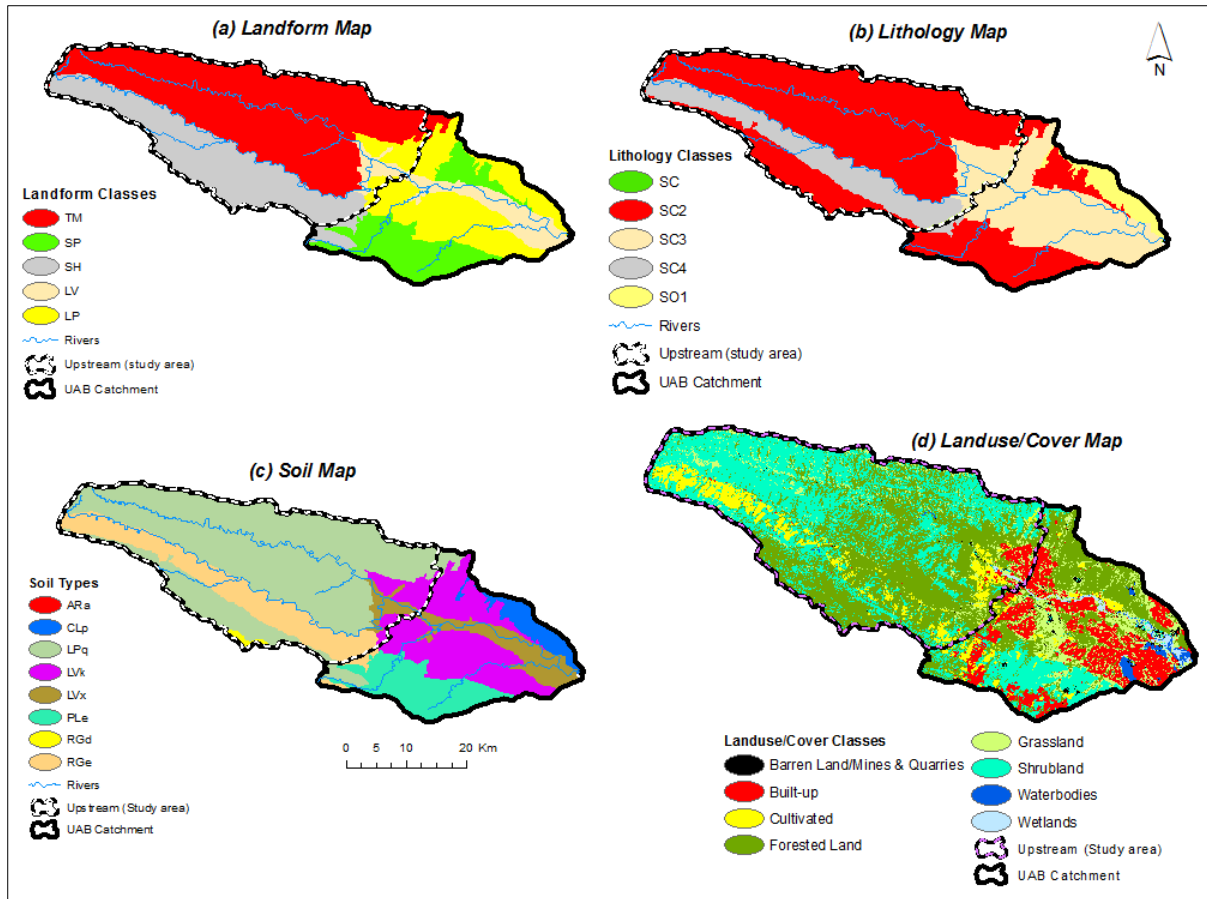


Figure 4.2. Maps drawn in ArcGIS showing landform, lithology, soil and land use type

4.2 Data quality control

Climate, streamflow, land use, soils and DEM datasets that were sourced could contain some ambiguous values and information that could affect the models' outputs. Therefore, data quality control which included screening and identifying missing values and gaps (climate and streamflow), re-projecting the spatial data (Land use, soil, and DEM) was adopted. After screening, all the missing values and gaps filled by -99.0.

4.3 Conceptual-perceptual model for groundwater recharge dynamics

According to Izady et al. (2014), developing a holistic qualitative conceptual model requires the combination of various datasets for example, existing topography, geology, lithology, land use/cover, analyses of existing hydro-meteorological data, stakeholder observations about hydrological events and processes (citizen science), field investigations, laboratory analyses of field measurements, published studies in the upstream area. In the upstream area of UAB, frameworks such as those of Brassington et al (2010), Izady et al (2014) and Walker et al (2019), were followed to develop an integrated qualitative conceptual model. Additionally, guidance within grey literature and textbooks contributed to the understanding of different

aquifer properties. The stages involved in developing a qualitative conceptual model for the upstream area are listed in (Figure 4.3).

The general methodology progressed from “desk study” to “qualitative conceptual model” development (Jha et al., 2010). To note here is that, in this study, citizen science though can be a key source of information to be considered during the formulation of a qualitative conceptual model (Brassington et al., 2010; Walker et al., 2019), it was not incorporated because of the financial expenses involved and the COVID-19 pandemic.

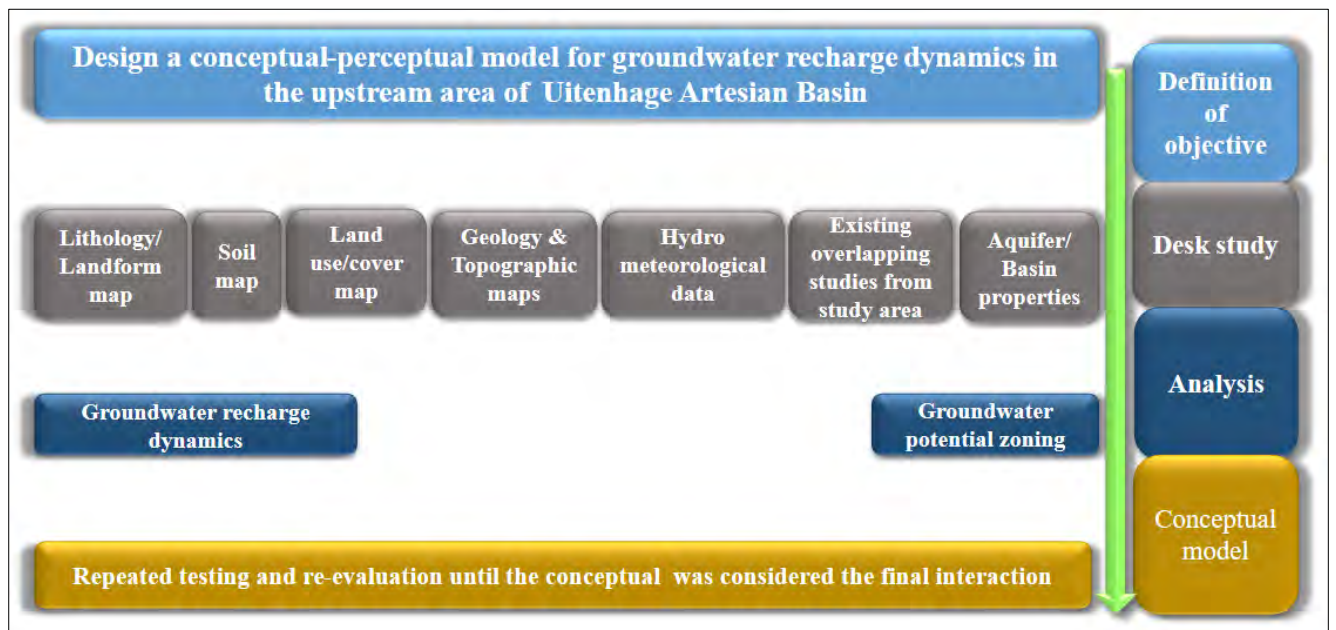


Figure 4.3. Methods involved in developing qualitative conceptual model

4.3.1 Geology map

The map that depicts the geology of the upstream was created by digitizing a published geology map (3324 Port Elizabeth; 1:250000-Geological Series, (see Figure 3.4)) in ArcMap 10.2.2 (Figure 4.4 and Table 4.6). Geological cross-section lines (i.e., AA', BB', CC', and DD') were then drawn over the digitized geological map using the drawing tool in ArcMap and saved as polylines.

These geological cross-section lines portray geological distributions with AA' representing the very upstream area, BB' mid upstream, CC' bottom part of the upstream, and DD', the downstream area. Furthermore, geological cross-sections with structural features were drawn using qProf (QGIS Plugin- to generate the profile from the digital elevation data), and strike and dip angles of the geological structures which were captured from the published geological

map were later used to manually sketch the vertical geological cross sections (i.e., AA', BB', CC', and DD') (Figure 4.4).

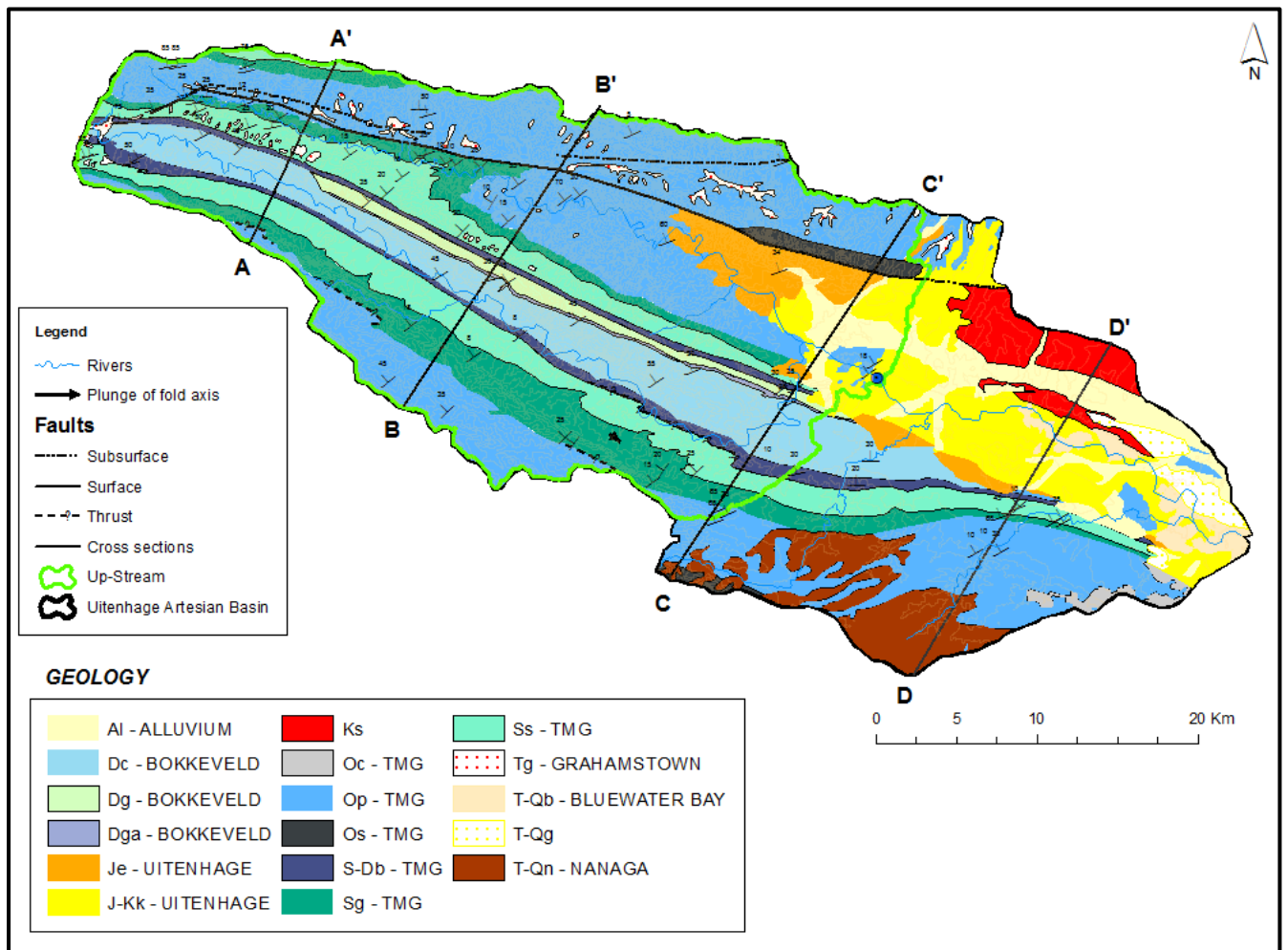


Figure 4.4. Map drawn in QGIS showing geological structures, classification and grouping (Adapted from Council of Geoscience, South Africa)

Table 4.6. Geological classification and grouping (Source: 3324 Port Elizabeth; 1:250000- Geological Map Series; Council of Geoscience, South Africa)

Geology type	Group	Subgroup	Formation	Lithology Description
Al	n/a	n/a	n/a	Alluvium
Tg			Grahamstown	High-level terrace gravel
T-Qb			Bluewater Bay	Alluvial sheet gravel and sand
T-Qg				Intermediate and low-level fluvial terrace gravel
T-Qn			Sundays River	Greenish-grey mudstone, sandstone
T-Qn			Nanaga	Aeolianite
Je	Uitenhage		Enon	Conglomerate, subordinate and mudstone
J-Kk			Kirkwood	Reddish and greyish mudstone, sandstone
Dga	Bokkeveld	Ceres	Gamka	Impure feldspathic sandstone
Dc			n/a	Undifferentiated
Dg			Gydo	Black shale, subordinate siltstones, fossiliferous
Op	TMG	n/a	Peninsula	Quartzitic sandstone
Os			Sardinia Bay	Quartzitic sandstone, subordinate shale, and conglomerate
S-Db		Nardouw	Baviaanskloof	Impure feldspathic sandstone
Sg			Goudini	Brownish weathering quartzitic sandstone
Ss			Skuweberg	Quartzitic sandstone, profusely cross-bedded
Oc		n/a	Cedarberg	Shale; arenaceous towards top

4.3.2 3D Topographic map

Using the UAB shapefile, Shuttle Radar Topography Mission-Digital Elevation Model (SRTM-DEM) data (Table 4.4) was clipped in ArcMap 10.2.2, software. Google Earth Pro aerial imagery (taken using on screen-Desktop technique on 1/3/2022) over the UAB was georeferenced in ArcMap 10.2.2 to appropriately match with the clipped SRTM-DEM map. Using hydrology tools in Arc Toolbox, a DEM Fill layer was created, and the filled DEM and the georeferenced image were then added into Arc Scene with the filled DEM as the source for base height while using the same vertical exaggeration factor to create a 3D. Fault system (i.e. surface, subsurface, and thrust), cross-section lines (i.e. AA', BB', CC', and DD'), and water movements were hypothetically superimposed on the generated 3D topographic surface map (see Figure 4.5).

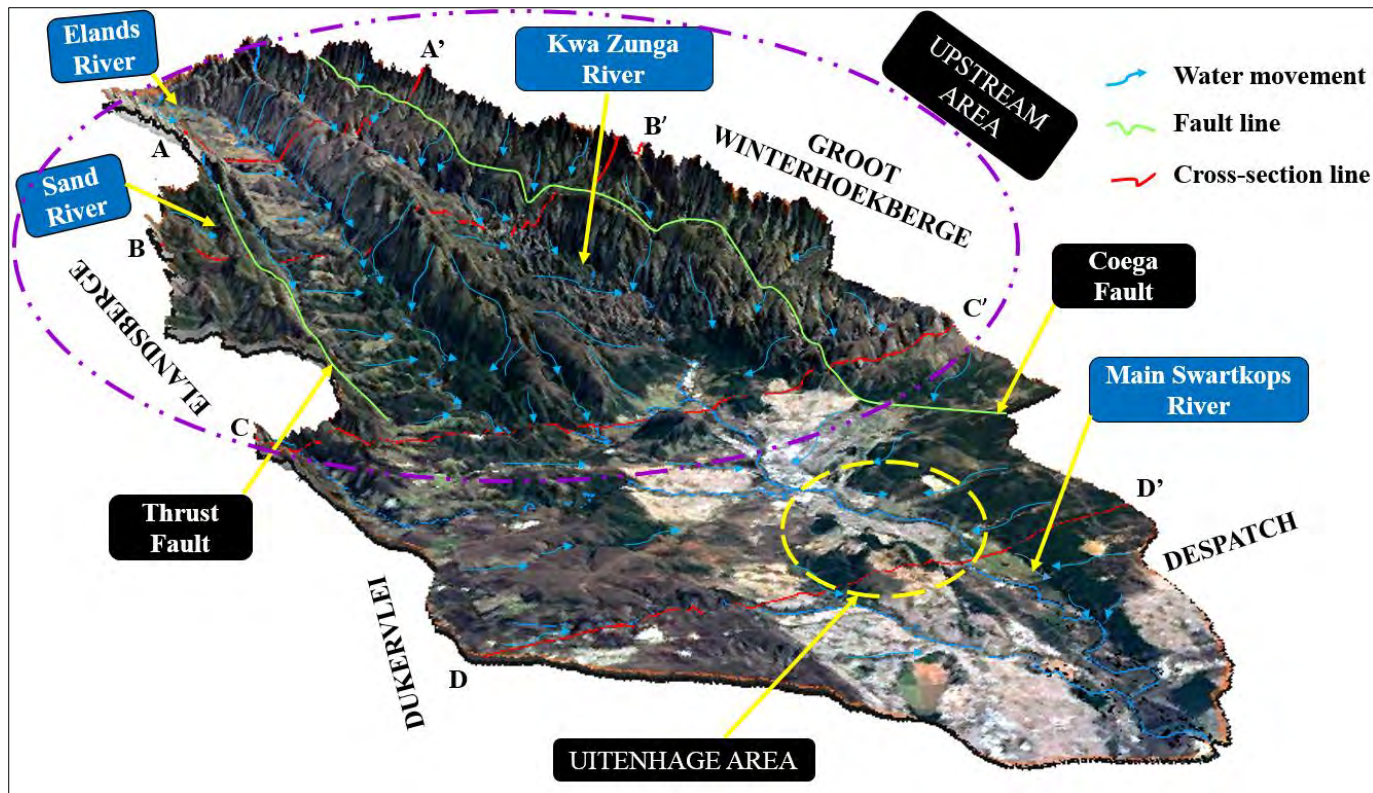


Figure 4.5. 3D topographic map drawn in Arc Scene showing superimposed water movement in the upstream area and cross section lines

4.3.3 Aquifer characterisation

Here groundwater level depth contours, aquifer yield type (primary and secondary), and transmissivity maps were prepared in ArcMap 10.2.2 using data from Table 4.3 and SOTERSAF database. From water level data points, (Table 4.3), meters below the surface (mbs) and meters above the mean sea level (mamsl), the points were interpolated using IDW technique in ArcMap 10.2.2 from which a contour tool from the Spatial Analysis section within ArcMap 10.2.2 was then used to generate the contour maps of different intervals.

4.3.4 Lineament density (LD)

Lineaments are surface linear elements found within the earth's crust which give an indication of underlying geological structures such as faults, fractures, or joints (Pradhan et al., 2010; 2006). These hydro-geological underground features can facilitate groundwater recharge, storage, and flow, influencing an area's groundwater potential. STRM-elevation data was used to create lineament networks in ArcMap 10.2.2 by applying the line density command analysis tool. The process involved creating four different hill shade maps, each with different azimuth and altitude values (chosen by the researcher). Each hill shade map was generated using a combination of two input variables: [315°, 45m for the first map]; [200°, 50m; for the second

map]; [100°, 60m; for the third map]; [50°, 90m; for the fourth map], as illustrated by [see also, <https://www.youtube.com/watch?v=sAKP19IbO70>] (Reuter and Nelson, 2009).

These four hill shade maps were used in sequence to identify lineament lines. The first hill shade map [315°, 45m] lays the foundation for the creation of lineament lines although it is less detailed due to the higher azimuth angle in relation to geological arrangement compared to the last hill shape map [50°, 90m] whose azimuth angle is lower. With the Editor Tool activated, lines seen over the four hill shade maps were digitized on-screen using ArcGIS 10.2.2 using the turning on and off layer technique. Using the Spatial Analysis Tool under line density command, the lineament density raster layer (Figure 4.6b) was created which was then reclassified into different by applying Equation 4.3.

$$LD = \sum Le / A \quad (\text{Equation 4.3})$$

Where LD , ($\frac{km}{km^2}$) refers to lineament density, Le (km) represents total length of all lineaments and $A(km^2)$ as unit area of the drainage area.

4.3.5 Drainage density (DD)

Using the hydrology tools in Arc Toolbox, a Filled DEM layer was created. Using the output of Filled DEM, a Flow Direction layer was created, which was thereafter used as an input layer to create a Flow Accumulation layer. This was then conditioned using the Conditional tool to remove outliers. The Conditioned Flow Accumulation (with an area about 39.5 Km²) and the Flow Direction layers were then used to generate a stream order layer. By applying the line density command of Arc Toolbox, a drainage density raster layer (Figure 4.6c) was created and then reclassified into classes using Equation 4.4.

$$DD = \sum Le / A \quad (\text{Equation 4.4})$$

Where DD , ($\frac{Km}{Km^2}$) is the drainage density, Le represents total the length of all streamlines and A (Km^2) as unit area of the drainage area.

4.3.6 Slope

From the clipped the SRTM-DEM map, a slope map was generated. The output map was then reclassified into five classes, according to variations in degree of the area (flat /valley plains to very steep areas) (Figure 4.6a).

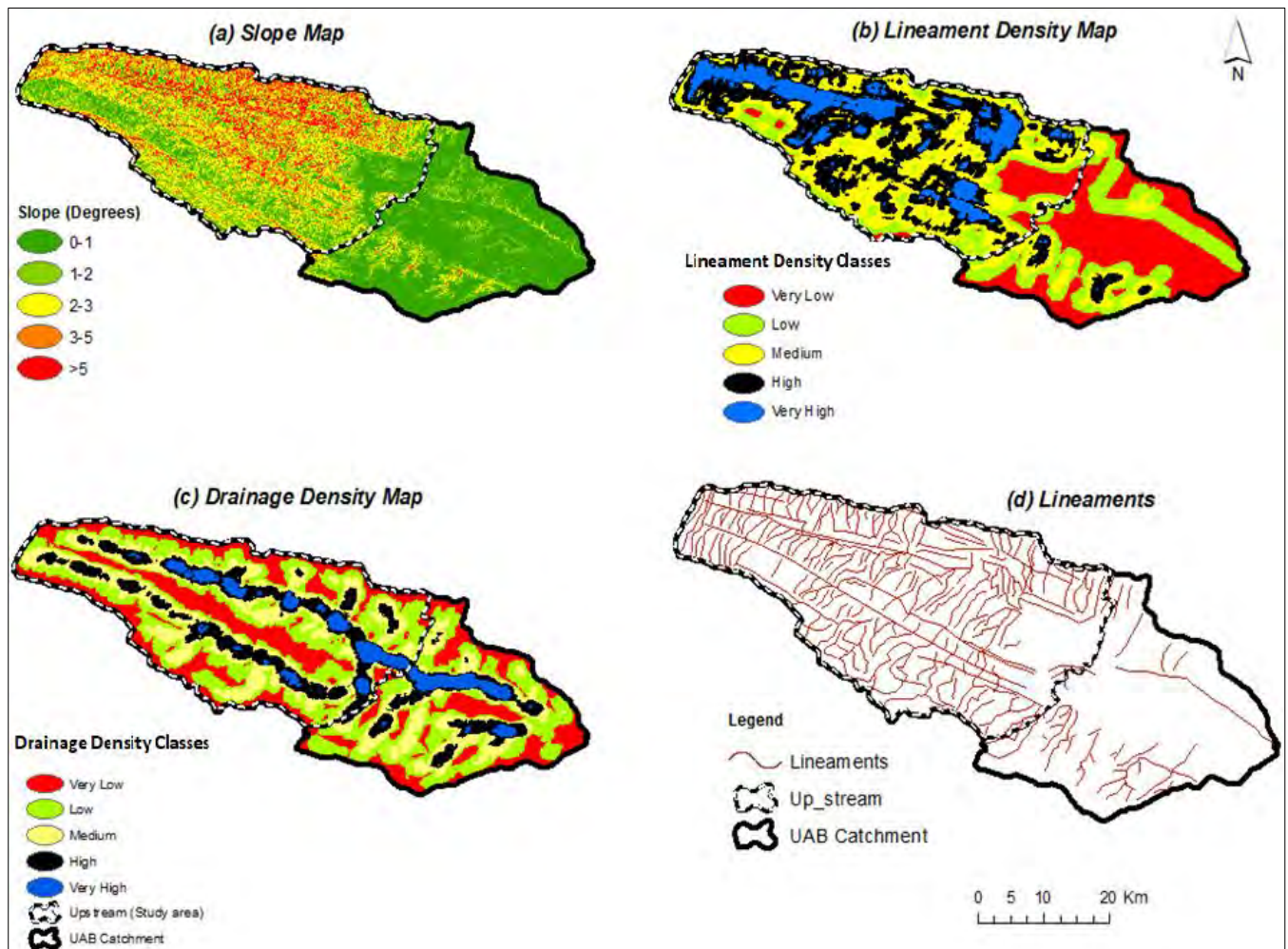


Figure 4.6. Maps drawn in ArcGIS showing slope, lineament density, drainage density and lineaments

4.3.7 Groundwater potential zoning and validation

Here groundwater potential zoning refers to demarcating areas which are assumed to have groundwater storage which can be abstracted over a given period and the storage can either be through direct or indirect recharge in conjunction with factors such as terrain, soils, geology, vegetation cover and climate. Groundwater potential zoning is of great importance for the protection of water quality and the management of groundwater resources (Kattimani et al., 2018). Identification of groundwater potential zones using any method depends on direct and

indirect analysis of observable features such as geology, soils, land use type, lineament density, geomorphology, and their hydrologic characteristics.

In the current study, a standard methodology to delineate groundwater potential zones using integrated GIS and multi-criteria decision making (MCDM) techniques was proposed were initially, six thematic layers (slope, drainage density, lineament density, land cover, landform, lithology, and soil) were considered. Some thematic layers such as soil types, lithology, land use type and landform were reprocessed and reclassified in ArcMap 10.2.2 to turn their features into values that could be combined and compared in a relative sense to other numerical thematic layers (drainage density and lineament density) (Table 4.7).

The weights and rank of these thematic (numerical) layers were then taken depending on their individual hydrologic characteristic on groundwater occurrence considering the works carried out by researchers such as (i.e., Baron,2000; Hughes and Parsons, 2007; Izady et al., 2012; Kattimani et al., 2018; Machiwal et al., 2011; Maclear 2001; Ndhlovu and Woyessa, 2021; Nolte et al., 2021; Tanner et al., 2019) and personal opinion about the upstream area. Weights of the thematic layers and their features were then normalized using Analytic Hierarchy Process (AHP) technique, a multi-condition algorithm designed and operated using MS Excel version 2013 (Goepel, 2019, 2013).

The AHP is a pairwise comparison matrix ranking tool that is commonly applied while assessing the magnitude of influencing factors (Ndhlovu and Woyessa, 2021). Here, eigenvalues attached to respective thematic layers were scrutinized and examined for consistency using a consistency ratio (CR) (Equation 4.5 and 4.6) as stated by Jha et al., 2010 and Kattimani et al., 2018. Kattimani et al., 2018 further elucidated that, to achieve reasonable consistency of thematic weights, the value of consistency ratio (CR) should be less than 10%, otherwise the corresponding weights should be re-evaluated to avoid inconsistency.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{Equation 4.5}$$

$$CR = \frac{CI}{RCI} \quad \text{Equation 4.6}$$

Where λ_{max} principal eigenvalue, CI consistency index, CR is consistency ratio, RCI random consistency index and n is the number of factors or criteria.

The AHP results (Table 4.7) were then used in amalgamation with other thematic layers within ArcMap 10.2.2 and then overlaid together using the Weighted Overlay tool to generate

groundwater potential index (GWPI). The GWPI was computed by using the weighted linear combination method (Equation 4.7).

$$GWPI = \sum_{w=1}^m \sum_{i=1}^n (w_j - x_i) \quad \text{Equation 4.7}$$

Where *GWPI* groundwater potential index, w_j normalised weight of the j^{th} thematic layer, x_i normalised weight of the i^{th} thematic feature, m total number of thematic layers and n is total number of classes in the thematic layer.

Thus, four groundwater potential zones were identified and demarcated in the upstream area, viz., ‘Poor’, ‘Fair’, ‘Good’ and ‘Excellent’ based on GWPI values (GWPI<0.4, 0.4<GWPI<0.6, 0.6<GWPI<0.8 and 0.8<GWPI<1.0) respectively. Although precipitation is presumably a main basis for groundwater recharge, in this study, it was not used as an input thematic layer during the zoning of groundwater potential areas, since topography, aspect and elevation can influence rainfall, these factors were considered separately in AHP, and thus somewhat compensates for not having good enough rainfall distribution.

Table 4.7. Ranking of influencing factors

Parameter	Classes	Groundwater prospect	Rank	Normalized Principal Eigen vector (%)
Slope Classes	Nearly level (0°-1°)	Very good	5	17.22
	Very gently sloping (1°-2°)	Good	4	
	Gently sloping (2°-3°)	Moderate	3	
	Moderately sloping (3°-5°)	Poor	2	
	Strongly sloping (≥5°)	Very poor	1	
Drainage density (Km/Km ²)	0-1.7	Very good	5	9.64
	1.7-3.4	Good	4	
	3.4-5.0	Moderate	3	
	5.0-6.7	Poor	2	
	6.7-8.4	Very poor	1	
Lineament density (Km/Km ²)	0-0.4	Very poor	1	15.2
	0.4-0.9	Poor	2	
	0.9-1.3	Moderate	3	
	1.3-1.7	Good	4	
	1.7-2.1	Very good	5	

Table 4.7 Continued....

Parameter	Classes	Groundwater prospect	Rank	Normalized Principal Eigen vector (%)
Land use /cover type	Barren land/mines & quarries	Very poor	1	12.44
	Built-up	Poor	2	
	Cultivated	Very good	5	
	Forested land	Good	4	
	Grassland	Moderate	3	
	Shrubland	Moderate	3	
	Waterbodies	Good	4	
	Wetlands	Good	4	
Landform	Dissected plain	Good	4	20.77
	High gradient mountain	Poor	1	
	Medium gradient hill	Moderate	3	
	Plain	Good	4	
	Valley floor	Very good	5	
Lithology	Sandstones	Good	4	15.83
	Shale	Very good	5	
	Siltstone, claystone	Poor	2	
	Limestone and other carbonates	Moderate	3	
	Clastic sediment	Poor	2	
Soil	Epipetric Calcisols	Good	4	8.9
	Lithic Leptosols	Moderate	3	
	Calcic Luvisols	Good	4	
	Chromic Luvisols	Poor	2	
	Gleyic Planosols	Poor	2	
	Arenic Regosols	Very good	5	
	Eutric Regosols	Very good	5	
	Albic Arenosols	Very good	5	

To validate demarcated groundwater potential zones, borehole data points with yield values (Table 4.3) were overlaid, and later checked with the generated potential map. Here, boreholes and wells that had poor yields were left out and the assumption made was that all the selected boreholes were sighted on areas with high potential of groundwater because of earlier assessments done by the drillers. It should be noted that the spatial distribution of boreholes and wells alone may not support groundwater potential mapping in isolation of other factors, in this case, the study also compared the generated groundwater potential zone map with the

generated aquifer type and yield map. Frequencies and percentages of boreholes and wells corresponding to individual groundwater potential zone were analysed. The technique is supported by different and previous studies that have incorporated borehole data for validations, such as (Jha et al., 2010; Mkali, 2020; Ndhlovu and Woyessa, 2021).

4.4 Using SWAT model to estimate groundwater recharge

The model has been used in various regions to provide holistic approaches to solving the problems facing the world’s water resources (Abbaspour et al., 2015; Izady et al., 2015; Sao et al., 2020). The current study applied a workflow as illustrated by Figure 4.7 in simulating hydrological processes which are key in determining recharge dynamics within the upstream area.

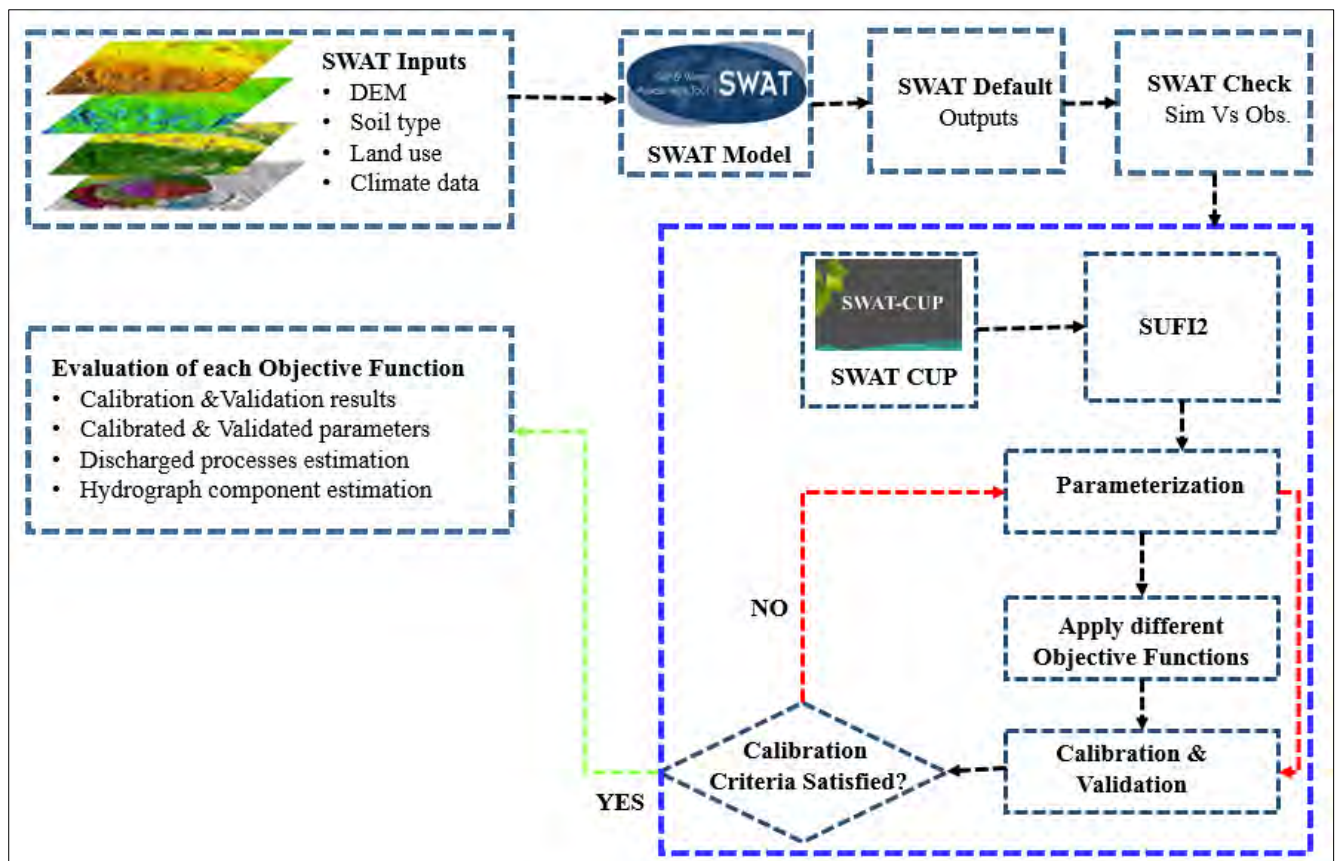


Figure 4.7. Workflow for estimating groundwater recharge using SWAT model

4.4.1 SWAT Inputs

Spatial coverage data which includes STRM-DEM, land cover and soil raster datasets as sourced (see Table 4.4, Table 4.9, and Figure 4.8) was used to set up the model. These datasets were clipped in ArcMap 10.2.2 using the upstream area boundary and reprojected to the

Universe Transverse Mercator (UTM) projection system, (a projection system that enables the SWAT model to read spatial data inputs correctly) (Gull and Shah, 2022). Integer grid codes for land cover types and soil type raster files were prepared using ArcMap 10.2.2. For the model to recognize various land cover types and soil types within its database, look-up tables that link the integer codes to the land cover type and soil type entries in the SWAT databases were prepared in MS. Excel software and saved in text format. In addition to the used SWAT soil database source, other soil parameters (Table 4.8) as available from SOTERSAF database (Dijkshoorn, 2003) were used.

The land cover parameters used upstream area were obtained from South African National Land-Cover (SANLC) database and were modified in the SWAT's internal database. The crop and vegetation information that the SWAT model currently uses was created under USA-specific conditions. One of the risks associated with applying the SWAT model to African circumstances is this, especially if the user wants to modify the database. Thus, the current study used locally available data from SOTERSAF database and local literature on crops and vegetation.

Table 4.8. Some soil parameters (Source: SOTERSAF)

Soil Class	Symbol	HYGRP	SOL_Z	SOL_BD	SOL_AWC	SOL_K
Lithic Leptosols	LPq	D	960	1.31	15	4.21
Leptic Regosols	RGe	D	910	1.18	9	8.12
Calcic Luvisols	LVk	C	100	1.6	0.175	10.71
Chromic Luvisols	LVx	D	1000	1.5	0.15	2.32
Arenic Regosols	RGd	D	490	1.25	17	7.88

HYGRP (hydrologic soil group; C[have moderately high runoff potential when thoroughly wet], D[have high runoff potential when thoroughly wet](National Resources Conservation Service, 2007), SOL_Z (Depth from soil surface to bottom layer), SOL_BD (Soil bulk density), SOL_AWC (Available soil water content) and SOL_K (Saturated hydraulic conductivity).

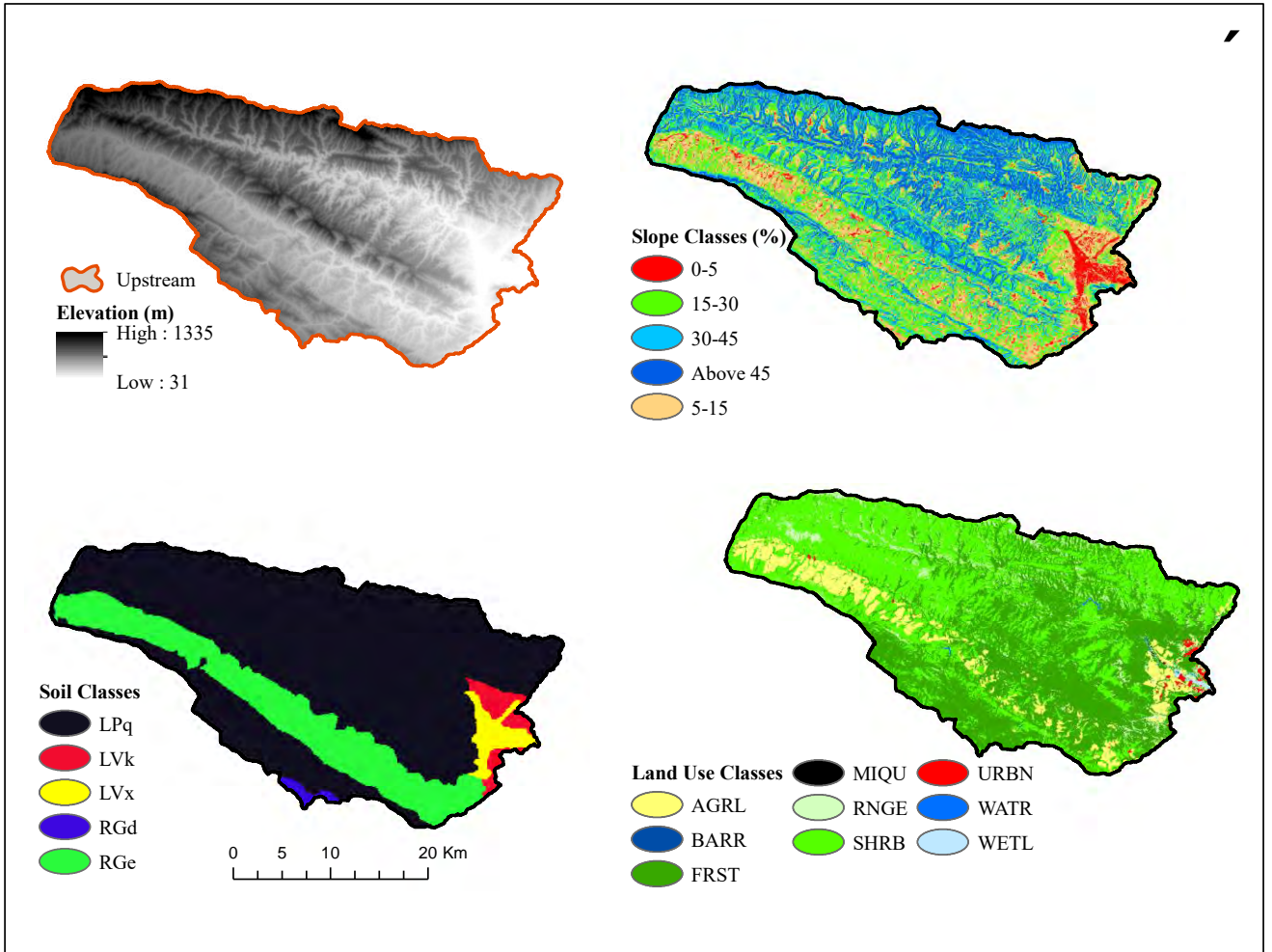


Figure 4.8. Maps drawn in ArcGIS showing SWAT spatial inputs

Table 4.9. Percentage composition of different spatial data classes

Land Use Type	Symbol	Area [ha]	% Watershed
Forest	FRST	37878.5	44.1
Shrub land	SHRB	35591.2	41.4
Grassland	RNGE	5046.9	5.9
Wetlands	WETL	164.2	0.2
Barren	BARR	69.5	0.08
Urban	URBN	569.6	0.66
Water	WATR	90.6	0.11
Agricultural	AGRL	6458.1	7.5
Mines-Quarries	MIQU	17.1	0.02
Total		85885.7	100
Soil Class	Symbol	Area [ha]	% Watershed
Lithic Leptosols	LPq	63480	73.9
Leptic Regosols	RGe	17215.8	20.1
Calcic Luvisols	LVk	2249.7	2.6
Chromic Luvisols	LVx	2327.2	2.7
Arenic Regosols	RGd	613	0.7
Total		85885.7	100
Slope Class (%)		Area [ha]	% Watershed
0-5		4541.5	5.3
5-15		17654.6	20.5
15-30		26674.2	31.0
30-45		18763.5	21.9
Above 45		18251.9	21.3
Total		85885.7	100

4.4.2 Setting up the SWAT Model

The Geographical Information System (GIS) version of SWAT, ArcSWAT2012 Version 2016_Rev64 hosted in the ArcGIS environment was used. With an approximated drainage area of 85885.7 ha (858.857 Km²), the upstream area was discretized into 19 sub-catchments that were again subdivided to generate 20 HRUs (Figure 4.9). The model was run and set-up to save outputs aggregated on a monthly time step from 1/1/1993 to 31/12/2021.

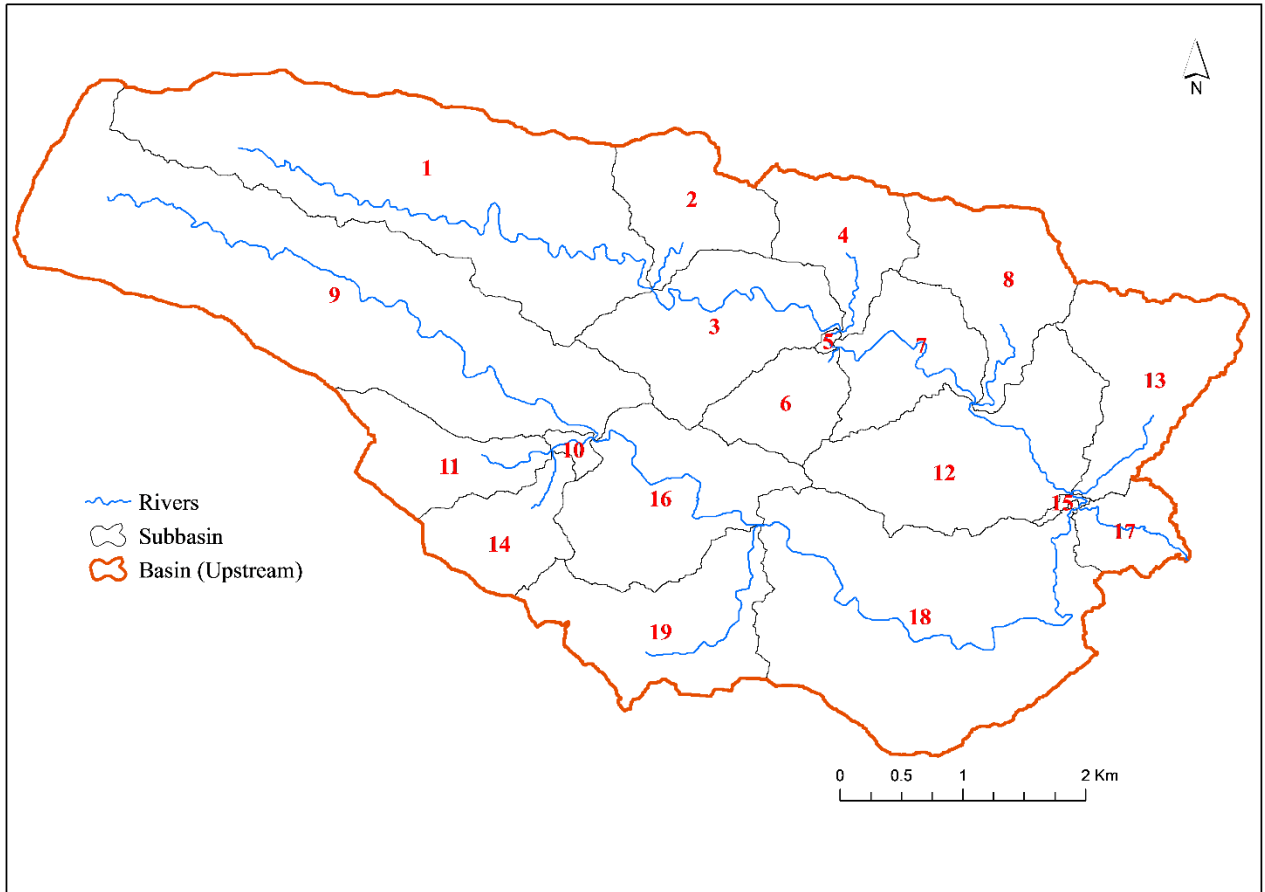


Figure 4.9. Map drawn in ArcGIS showing discretized sub-basin of the upstream area

4.4.3 SWAT Model calibration and validation processes

The SWAT Error Checker [Version 1.2.0.9; 2017 Release] program was used to scan the model set-up. After removing potential model problems, the model was then subjected to automatic calibration and validation using version 5.1.6 of SWAT-CUP 2012. This version (Figure 4.7) is a generic stand-alone software interface that was designed to provide calibration and validation evaluations together with other analyses (Abbaspour et al., 2007; Bennour et al., 2022; Sao et al., 2020; Senent-Aparicio et al., 2017; Tejaswini and Sathian, 2018). It includes various evaluation methods such as Sequential Uncertainty Fitting algorithm-2 (SUFI-2), Generalised Likelihood Uncertainty Estimation (GLUE), and Parameter Solution (PARASOL), among others (Tejaswini et al., 2018).

Studies of, Abbaspour et al (2015, 2007); Bennour et al (2022); Mehan et al (2017); Sao et al (2020) and Senent-Aparicio et al (2017) highlighted that SUFI-2 is among the best evaluation methods in SWAT-CUP and it has been globally applied to carry out various SWAT model analyses.

Using SWAT-CUP- SUFI-2 uncertainty approach (Abbaspour, 2015), SWAT model outputs were calibrated for a 17 year period, from 1993 to 2009, and later validated for a period of 11 years, 2010 to 2021, using monthly streamflow data at a streamflow gauge located at an outlet in sub-basin 17 (Figure 4.9). Here, sixteen parameters with their multiplier or scaler values, that are key for groundwater flows and groundwater recharge dynamics were selected during the calibration period (Table 4.10).

These were categorized as; groundwater parameters, soil water parameters, surface runoff parameters, canopy parameters, and evaporative parameters. NSE was used as the objective function, and 5 iterations of 500 simulations per iteration (2500 runs total) were performed. The iteration that had better objective function value was selected to be the output of the calibration process. The output parameter set was later used during the validation process. Generated SWAT results for each sub-basin were manually added onto the created attributes of the sub-basin shapefile in ArcMap 10.2.2 to facilitate visual representation of different water balance components in the upstream area.

Table 4.10. Multipliers or scalers for parameter values during calibration

#Parameter	Parameter description	Fitted value	Min value	Max value
R_CN2.mgt	Run off curve number (mm)	-0.195	-0.200	-0.195
R_ALPHA_BF.gw	Base flow alpha factor (days)	0.771	0.000	0.900
A_GW_DELAY.gw	Groundwater delay (days)	127.29	30.00	500.00
A_GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur (mm)	3.415	0.000	5.000
R_SOL_AWC.sol	Available water capacity of the soil layer	0.059	0.000	0.100
R_SOL_Z.sol	Depth from soil surface to bottom layer	-0.242	-0.250	0.250
A_CANMX.hru	Maximum canopy storage	86.280	0.000	120.00
A_GW_REVAP.gw	Groundwater revap coefficient	0.012	0.000	0.100
V_REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur (mm)	14.450	0.000	50.00
A_ESCO.hru	Soil evaporation compensation factor	0.003	0.000	0.010
R_SLSUBBSN.hru	Average slope length	0.238	-0.250	0.250
A_EPCO.hru	Plant uptake compensation factor	0.303	0.000	0.350
A_SURLAG.bsn	Surface runoff lag time	19.500	0.000	20.00
R_SOL_K.sol	Saturated hydraulic conductivity ($\mu\text{m/s}$)	35.055	0.000	45.000
R_SOL_BD.sol	Moist bulk density (g/mL)	0.063	0.000	0.100
A_RCHRG_DP.gw	Deep aquifer percolation fraction	0.257	0.000	1.000

A_ absolute parameter, R_ original parameter is multiplied by (1+ optimized value) and V_ replace the parameter value (Abbaspour et al., 2007; Izady et al., 2015)

4.4.4 SWAT Model Performance

Similar to other studies for example; Dekongmen et al (2022); Izady et al (2015); Senent-Aparicio et al (2017) and Yifru et al (2020), SWAT's capability to represent various natural processes was assessed using; R^2 , NSE, PBIAS and Kling-Gupta efficiency (KGE) (Table 4.11 and Table 4.12). Additional details of these functions is found in related studies of (Abbaspour, 2015; Abbaspour et al., 2007).

Table 4.11. List of objective functions selected for the SWAT and Pitman model (Source: Gupta and Lehal, 2009; Moriasi et al., 2012; Nash and Sutcliffe, 1970)

Objective Functions	Equation	Value range	Acceptability threshold
Percent Bias (<i>PBIAS</i>)	$PBIAS = 100 * \frac{\sum_{t=1}^T (Q_m^t - Q_o^t)}{\sum_{t=1}^T Q_o^t}$	$-\infty$ to ∞	$ PBIAS \leq 25\%$ Satisfactory
Coefficient of determination (R^2)	$R^2 = \left[\frac{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)(Q_m^t - \bar{Q}_m)}{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)^2 \sum_{t=1}^T (Q_m^t - \bar{Q}_m)^2} \right]^2$	0 to 1	$R^2 \geq 0.6$ Satisfactory
Nash Coefficient of Efficiency (<i>NSE</i>)	$NSE = 1 - \left[\frac{\sum_{t=1}^T (Q_o^t - Q_m^t)^2}{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)^2} \right]$	$-\infty$ to 1	$NSE \geq 0.5$ Satisfactory
Kling-Gupta efficiency (<i>KGE</i>)	$KGE = 1 - \sqrt{(r - 1)^2 + \left(\frac{S_m}{S_o} - 1\right)^2 + \left(\frac{\bar{Q}_m}{\bar{Q}_o} - 1\right)^2}$	$-\infty$ to 1	$KGE \geq 0.5$ Satisfactory

Where Q_o^t is the observed value for time step t, Q_m^t is the modelled value for time step t, \bar{Q}_o and \bar{Q}_m are the means of the observed and modelled values for time steps t=1 to T respectively, S_o and S_m are standard deviations of the observed and modelled values for time steps t=1 to T respectively, and r is Pearson's correlation coefficient between the Q_o^t and Q_m^t datasets for t=1 to T.

Table 4.12. Criteria for assessing the performance of the two models

Performance evaluation criteria				
	Very Good	Good	Satisfactory	Unsatisfactory
R^2	$R^2 > 0.85$	$0.75 < R^2 \leq 0.85$	$0.60 < R^2 \leq 0.75$	$R^2 \leq 0.60$
<i>NSE</i>	$NSE > 0.80$	$0.70 < NSE \leq 0.80$	$0.50 < NSE \leq 0.70$	$NSE \leq 0.50$
<i>PBIAS</i>	$PBIAS < \pm 5$	$\pm 5 \leq PBIAS < \pm 15$	$\pm 15 \leq PBIAS < \pm 25$	$PBIAS \geq \pm 25$
<i>KGE</i>	$KGE > 0.75$	$0.75 < KGE \leq 0.50$	$0.50 < KGE \leq 0.00$	$KGE \leq 0.00$

(Source: Sao et al., 2020; Senent-Aparicio et al., 2017)

4.5 Using the Modified Pitman Model to estimate groundwater recharge

Since its modification to incorporate groundwater recharge and discharge routines, the Modified Pitman model has become a known and extensively applied tool in water resource management and studies in countries that are below the equator on the African continent (Hughes & Forsyth, 2006; Hughes, 2004a; Kapangaziwiri et al., 2011; Sawunyama, 2008; Tanner, 2013). The workflow as illustrated by (Figure 4.10) was followed to simulate hydrological processes that are key in estimating groundwater recharge dynamics.

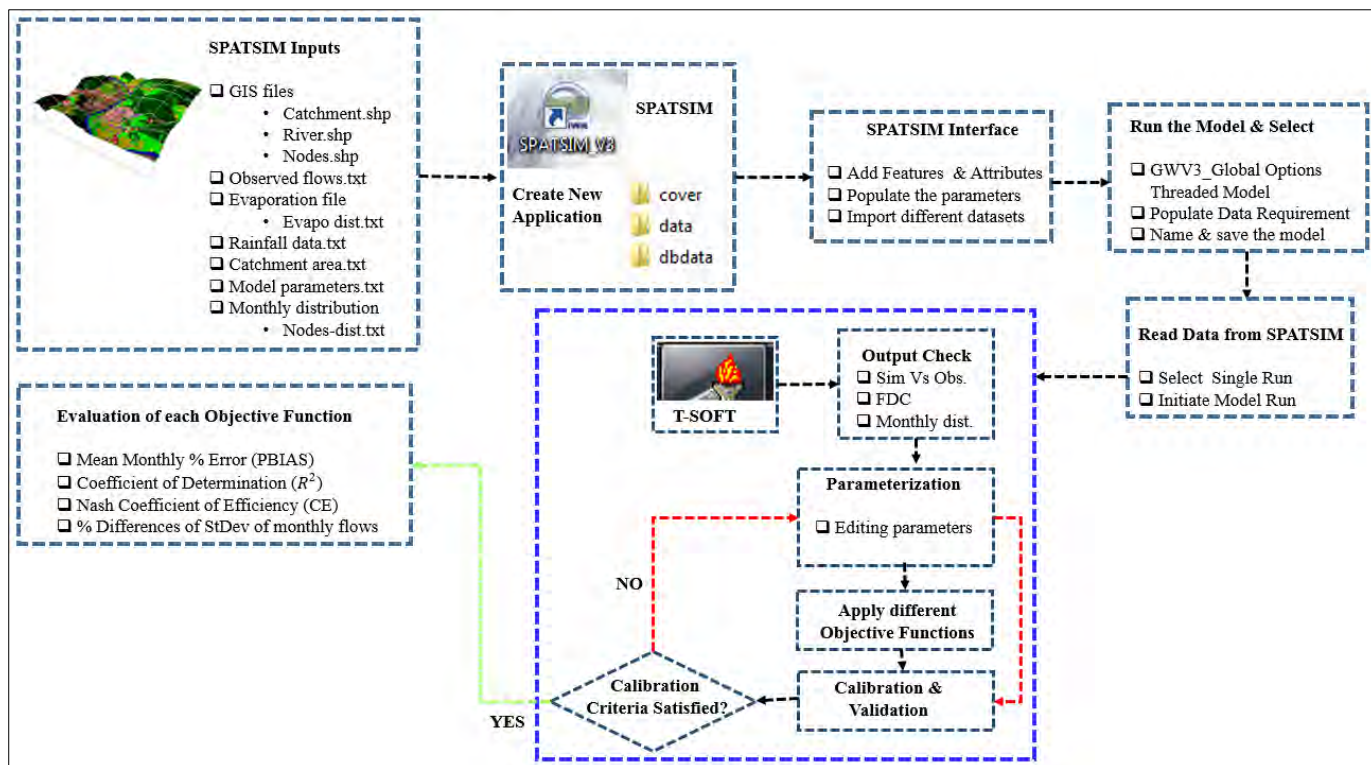


Figure 4.10. Workflow for estimating groundwater recharge using Modified Pitman model

4.5.1 SPATSIM Inputs

The modified Pitman version (GWv3 Global Threaded Model) that runs on SPATSIM requires a set of inputs. In the current study, the sub-basin shapefile was obtained from the Arc SWAT delineated watershed, river shapefile (clipped using sub-basin shapefile in ArcMap 10.2.2), and sub-basin Nodes which accommodate data for each sub-basin [M10A (7); M10B (7) and M10C (5)] were manually created in ArcMap 10.2.2. Attribute fields indicating the names and descriptions of each sub-basin were created and populated, and these names were given to the sub-basin Nodes. Using ArcMap10.2.2, the datasets were reprojected to Geographical Coordinate System (GCS) (a projection system that enables SPATSIM to read spatial data

inputs correctly, Pitman Manual Guide). Sub-basin catchment area values were computed in ArcMap 10.2.2 by adding a field column in the sub-basin attribute table which was later named “(Area_Km²).

Aggregated monthly output rainfall datasets from the SWAT model (i.e., 19 sub-basins) were externally arranged in hydrological year format and saved as text files for each sub-basin. The Pitman model requires S-pan evaporation, in this case, since SWAT model uses spatially explicit map inputs of topography, land cover, soil types and climate data to drive an automated set-up of modelled units and parameters (Scott-Shaw et al., 2020), potential evapotranspiration (PET) time series generated by the SWAT model for each sub-basin were obtained externally, a 1.2 conversion factor was then used to convert SWAT-generated PET time series to S-pan evaporation time series which were then prepared as Pitman model input sub-basin text files.

4.5.2 Modified Pitman Model Setup

The Institute for Water Research (IWR)-Rhodes University version of Pitman, GWv3 Pitman version (GWv3 Global Threaded Model) (Hughes and Forsyth, 2006; Hughes, 2004a) was chosen and applied on the initial model run type called “Single Run” to simulate hydrological processes that are responsible for groundwater recharge dynamics in the upstream area (see Figure 4.10). Since there are many parameters in the Modified Pitman model (i.e. 41 parameters), however, here much emphasis was put on the major parameters that influence groundwater recharge volumes with surface discharge within 19 sub-basins (Figure 4.10), (i.e. RDF, PI1s, PI2s, AFOR, FF, PEVAP, SL, R, D.Dens, RWL, among others; see details from Table 2.2; Hughes et al., 2006; Kapangaziwiri et al., 2011; Sawunyama, 2008; Tanner, 2013; Tshimanga et al., 2011; Tumbo, 2014). In the current study, a total simulation span for calibration (1993 to 2009) and validation (2010 to 2021) monthly was used.

Since Modified Pitman model has conceptual properties, individual sub-basin (19 sub-basins, Figure 4.11) generated from the three main quaternary catchments, (Figure 3.1) contained its rainfall, evapotranspiration demand data, and model parameter sets (Table 4.13) that were used to signify the main hydrological processes. Percentage area of vegetation (AFOR) was calculated for each of the 19 sub-basins from the land cover map and assigned to each sub-basin. Drainage density (D.Dens) was calculated for each of the 19 sub-basins from the drainage density map created in ArcMap and compared with values from the National Quaternary database (WR2012).

Values for transmissivity and storativity were obtained from the National Quaternary Database (WR2012) were assigned to the 19 sub-basins using the three major quaternary catchments through which each sub-basin fall. Annual Pan Evaporation (PEVAP) values were computed for each sub-basin using the converted SWAT-generated S-pan evaporation. The other set of parameters (Table 4.13) for the three quaternaries that aggregate the 19 sub-basins were obtained from the regionalized calibrated values from (WR2012) database.

Table 4.13. Some of the initial model parameter set used at quaternary catchment scale

(Source: Bailey and Pitman, 2016)

Parameters	M10A	M10B	M10C
RDF	1.280	1.280	1.280
AFOR	0.500	55.00	2.000
FF	1.400	1.400	1.400
PEVAP	1600	1600	1550
ZMIN	20.000	20.00	20.00
ZAVE	0.500	0.500	0.500
ZMAX	360.000	360.000	360.000
ST	100.000	100.000	100.000
FT	5.000	5.000	5.000
SL	0.000	0.000	0.000
POW	3.000	3.000	3.000
R	0.500	0.500	0.500
GW	5.000	5.000	5.000
GPOW	3.000	3.000	3.000
D.Dens	0.400	0.400	0.400
T	20.50	10.800	117.3
S	0.001	0.001	0.001
RWL	75.000	75.000	75.000
RSF	0.400	0.400	0.200

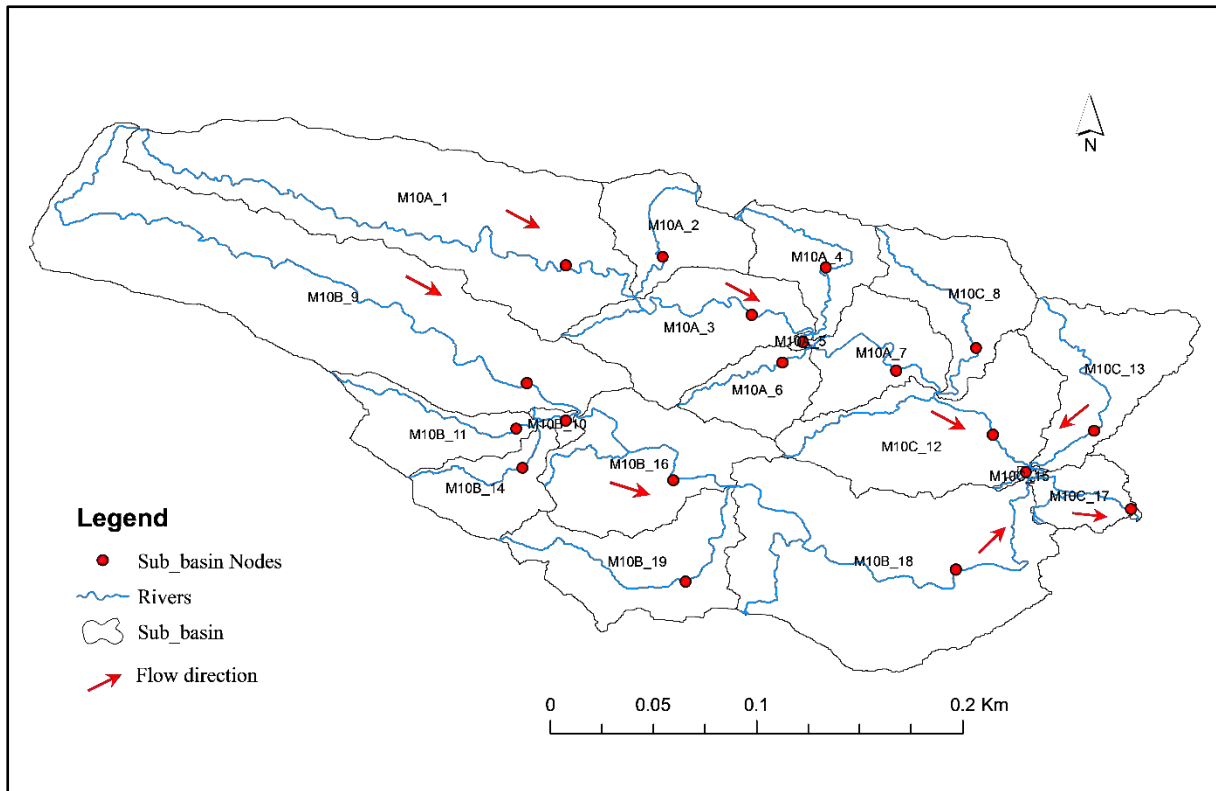


Figure 4.11. Map drawn in ArcGIS showing discretized sub-basins and their interactions with flows

4.5.3 Modified Pitman Model calibration and performance measures

Regionalized values were used as initial starting parameter values after which manual calibration was done by adjusting the parameter values until satisfactory threshold values of performance statistics were obtained (see Table 4.11). The generated Pitman water balance components (i.e., mean annual precipitation, potential evapotranspiration, base flow among others) for each sub-basin were manually added onto the created attributes of the sub-basin shapefile in ArcMap 10.2.2 to facilitate the spatial representation of the hydrological processes in the upstream area. Based on previous model application studies, (Hughes et al., 2006; Kapangaziwiri et al., 2011; Sawunyama, 2008), acceptable variable range values and standard performance measures (Table 4.11 and Table 4.12) were used to evaluate Pitman model performance in the current study.

4.6 Time series analysis of estimated groundwater recharge

Parametric and Non-parametric methods have been developed to detect trends in hydro-meteorological time series studies. Mann-Kendall statistical test (MK), a non-parametric method (Ayugi et al., 2020; Gocic and Trajkovic, 2013; Ongoma et al., 2018) was used to detect trends at 5% significance level in the estimated Pitman and SWAT models groundwater

recharge of the upstream area. The main aim of the MK test is to evaluate if there exists a statistical monotonic upward or downward trend of the variable over time (Gocic and Trajkovic, 2013). Using R software version 4.3.0, the MK test statistics S was calculated using equations 4.8 and 4.9.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad \text{Equation 4.8}$$

Where n is the number of data points, x_i and x_j are the data values in time series i and j ($j > i$), $\text{sgn}(x_j - x_i)$ is the sign function that is obtained from equation 4.9.

$$\text{sgn}(x_j - x_i) = \begin{cases} +1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \end{cases} \quad \text{Equation 4.9}$$

Where positive values of S indicate increasing trend while negative S values show decreasing trends.

4.7 Assess the value of application of the two hydrological models

The value of application of the modified Pitman and SWAT models was assessed concerning their capabilities to generate monthly sub-basin water balance components. Observed discharge values were used to compare the streamflow prediction performance between the Modified Pitman and SWAT models based on the following statistics, R^2 , NSE , $PBIAS$ and KGE . (Table 4.11 and Table 4.12) (Shi et al., 2011). To better understand how well the models captured the hydrologic behaviour generating high and low flows, modelled flows for five quartiles were compared with those of the observed (Safeeq et al., 2014). Furthermore, some of the generated water balance components were compared with those obtained from local recharge estimate studies (Table 2.1) and estimated values from Bailey and Pitman, 2016; and Groundwater Assessment Phase Two (GRAII) to determine if modelled recharge rate values were within an acceptable range.

CHAPTER FIVE

PRESENTATION OF RESULTS

5.1 Understanding groundwater recharge dynamics using Conceptual-Perceptual model

5.1.1 Geology

According to geology distribution, Table Mountain Group (TMG) characterised with fractured (Figure 5.1), and water-bearing rock outcrops dominates almost the entire upstream area (Figure 5.2). The geology classification is associated with two formations, Peninsula and Nardouw, which are irregularly folded, faulted, and confined downslope by the overlying Uitenhage Group (aquiclude) causing the artesian conditions in the downstream area. Upstream area also has syncline-anticline fold axes (AA' and BB'; Figure 5.2) which are primarily orientated northwest-southeast, a mechanism that channels the flow of surface water and subsurface water from the high mountain recharge areas to downslope aquifer areas (Figure 5.2).

Eland's valley sits in a syncline dominated by Bokkeveld geology group along the valley floor with Nardouw TMG rock outcropping at the margins (Figure 5.1). These formations usually don't feed the floodplain and alluvium aquifers directly, but they supplement mountain tributary streams that bring inflows from the Peninsula rock outcrops higher up in the mountains (Figure 5.2). The Uitenhage group is more dominant in the lower section (CC' and DD') of the study and it includes alluvium and floodplain material that form a relatively small primary aquifer.



Figure 5.1. Preferential fracture zones common in TMG areas (Adapted from Wu, 2005)

The fractured nature of the rock in the study area is in part due to several structural fault systems (e.g., subsurface, surface, and thrust) (Figure 5.2). The Coega Fault, a large surface fault is a predominant geological structure, orientated northwest-to-southeast towards the sea (downstream) and it is surrounded by highly fractured TMG rock. The feature is thought to be cemented by minerals that concentrated and solidified out of water that was trapped over a long period of time.

This result into deep groundwater being forced upward against a vertical aquiclude, thus acting as a pathway for groundwater flow (Figure 5.2), which may explain the artesian conditions observed in the downstream area of Uitenhage Artesian Basin. The TMG fault and lineament structures (Figure 4.6d) found in upstream area are localized zones of recharge with preferential flow characteristics resulting from extensive fracturing of the TMG rocks in the area (Figure 4.5 and Figure 5.1).

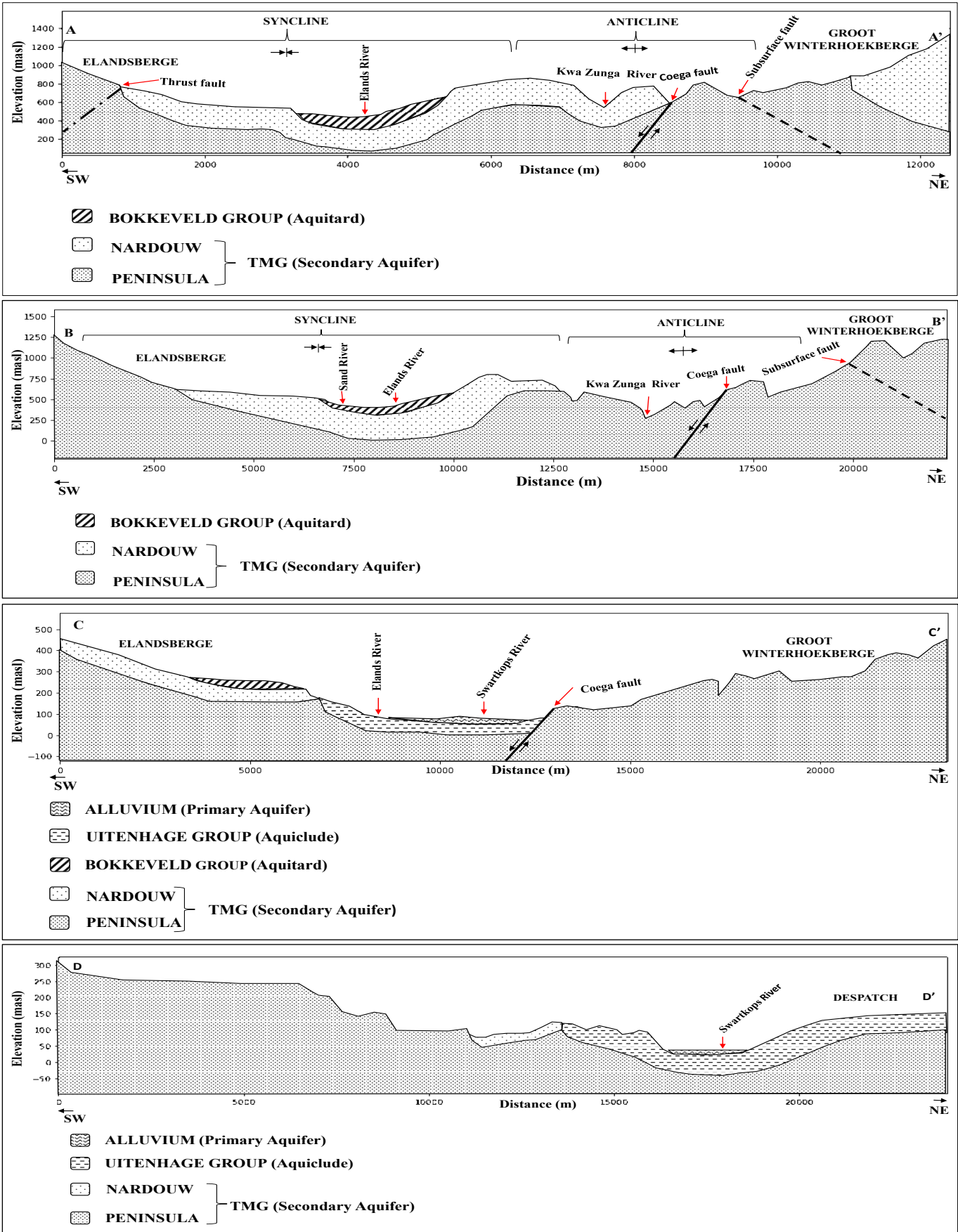


Figure 5.2. Vertical cross sections drawn across the study area

5.1.2 Aquifer properties

Here two aquifer types; type a-intergranular (primary or porous sandy aquifer) and type b-fractured (secondary aquifer), were identified in the upstream area (Figure 5.3a). Table 5.1 and Figure 5.3b indicate that the highest yield (>5.0 l/s) and transmissivity ($>16.8m^2/d$) are associated with a secondary fractured aquifer system situated just at the boundary of the upstream area and downstream of UAB. This aquifer type is highly fractured with outcrops of TMG providing substantial lateral recharge, both through surface-channel seepage and through subsurface percolation. It accounts for the high-yielding and high transmissivity characteristics of the type of aquifer and thus explains the existence of artesian conditions in the downstream area near the boundary of the upstream area of UAB.

Based on data from Table 4.3, drawn groundwater level contour maps (Figure 5.3c and Figure 5.3d) represent the northwest-southeast flow path as the general directional flow of surface and subsurface water following the topographic gradient from the mountainous upstream area towards the flatter downstream area. These structural orientations are responsible for the channelling of all surface and subsurface water flows emanating from the mountainous areas of the upstream area toward the downstream area of UAB and thus responsible for the recharge of downstream groundwater store.

Table 5.1. Aquifer type and characteristics (Source: Adapted from SOTERSAF Database)

Aquifer ID	Aquifer Name	Aquifer Type	Yield (l/s)	Transmissivity (m^2/d)	Ave Transmissivity (m^2/d)
1	Intergranular (primary)	Type a	0.1 – 0.5	0.09 – 0.8	0.445
2	Fractured (secondary)	Type b	0.0 – 0.1	0.0 - 0.09	0.045
3	Fractured (secondary)	Type b	0.1 – 0.5	0.09 – 0.8	0.445
4	Fractured (secondary)	Type b	0.5 – 2.0	0.8 – 4.93	2.865
5	Fractured (secondary)	Type b	>5	>16.8	16.8

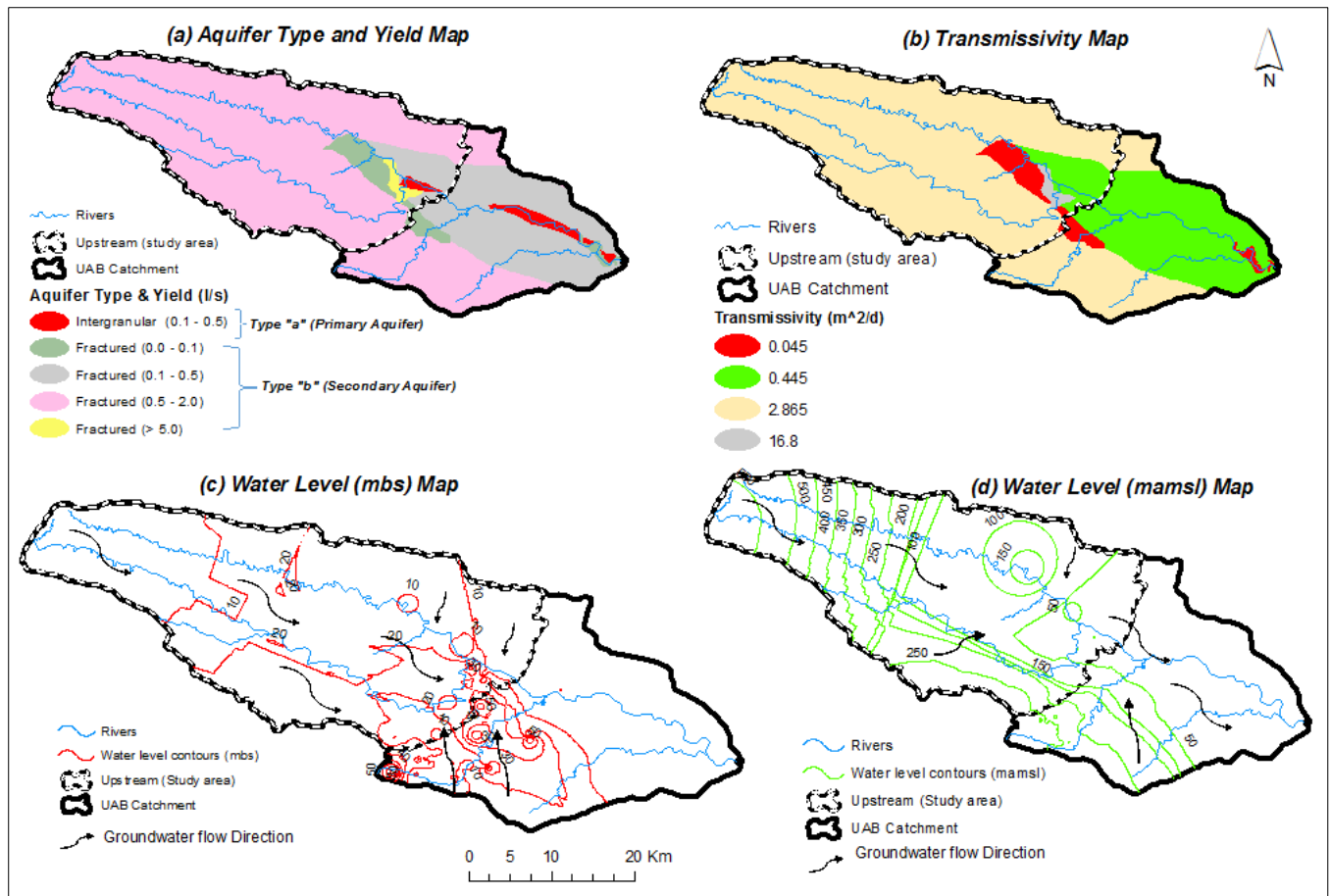


Figure 5.3. Map drawn in ArcGIS showing aquifer properties and classification (Source: Adapted from Maclear, 2001 and SOTERSAF Database)

5.1.3 Groundwater potential zoning

Under this section, groundwater potential zones were demarcated and classified into four classes (Figure 5.4). The generated map indicates that areas within Elands valley downwards to the section where upstream area joins the downstream area had Excellent to Good groundwater potential in general and this is attributed to the syncline structure along the area under investigation (Figure 4.5 and Figure 5.2), low slope gradient, relatively good soils (Eutric Regosols) coupled with the Bokkeveld and Nardouw geological formations which are known to be good groundwater stores with good aquifer yield and transmissivity (Figure 5.3a and Figure 5.3b).

Additionally, the fractured layering of the TMG (water-bearing rocks) in the area suggests Good and Excellent zones would be found along the Elands River valley downwards. Though rainfall in the upstream area and across the entire UAB showed higher levels of variability as was stated by Maclear, 2001, it was observed that areas with Good to Excellent groundwater

potential zones also had higher rainfall compared to those which are Fair to Poor as shown with the isohyets contour values that were superimposed on the groundwater potential zone map (Figure 5.4). Based on the mapping, approximately 8.7% of upstream area is in Excellent zone, 65.4% in Good, 25.8% on fair, and 0.01% on Poor groundwater potential zones (Table 5.2 and Figure 5.4).

For validation of the groundwater potential zone, results from (Table 5.3 and Figure 5.5) show that approximately 69.7% of the total number of boreholes, wells and springs are found within Good and Excellent zones with high yield rates that range from 3.8 to 21.0 l/s. hence confirming the highest potential of groundwater. Furthermore, the generated groundwater potential zone map (Figure 5.4) was compared with the generated aquifer type and yield map (Figure 5.3a) and a clear pattern where aquifers with highest yields (2.0 to more than 5 l/s) were found suited in zones that are classified as Good and Excellent.

Table 5.2. Groundwater potential zones for upstream area of UAB

Sr. No	GWPI	Potential zones	Area (Km ²)		Percent (%)		Comments
			UAB	Upstream area	UAB	Upstream area	
1	<0.4	Poor	0.1	0.1	0.01	0.01	Low potential for groundwater recharge
2	0.4-0.6	Fair	269.5	227.7	19.3	25.8	Sufficient potential for groundwater recharge
3	0.6-0.8	Good	1022.4	576.7	73.7	65.4	High potential for groundwater recharge
4	0.8-1.0	Excellent	95.1	76.9	6.9	8.7	Very high potential for groundwater recharge
Total			1387.1	881.4	100	100	

Table 5.3. Frequency and percentage of boreholes and wells within potential zones

Potential Zone	Number of boreholes & Wells	Percent (%)
Poor	0	0
Fair	26	30.2
Good	58	67.4
Excellent	2	2.3
Total	86	100

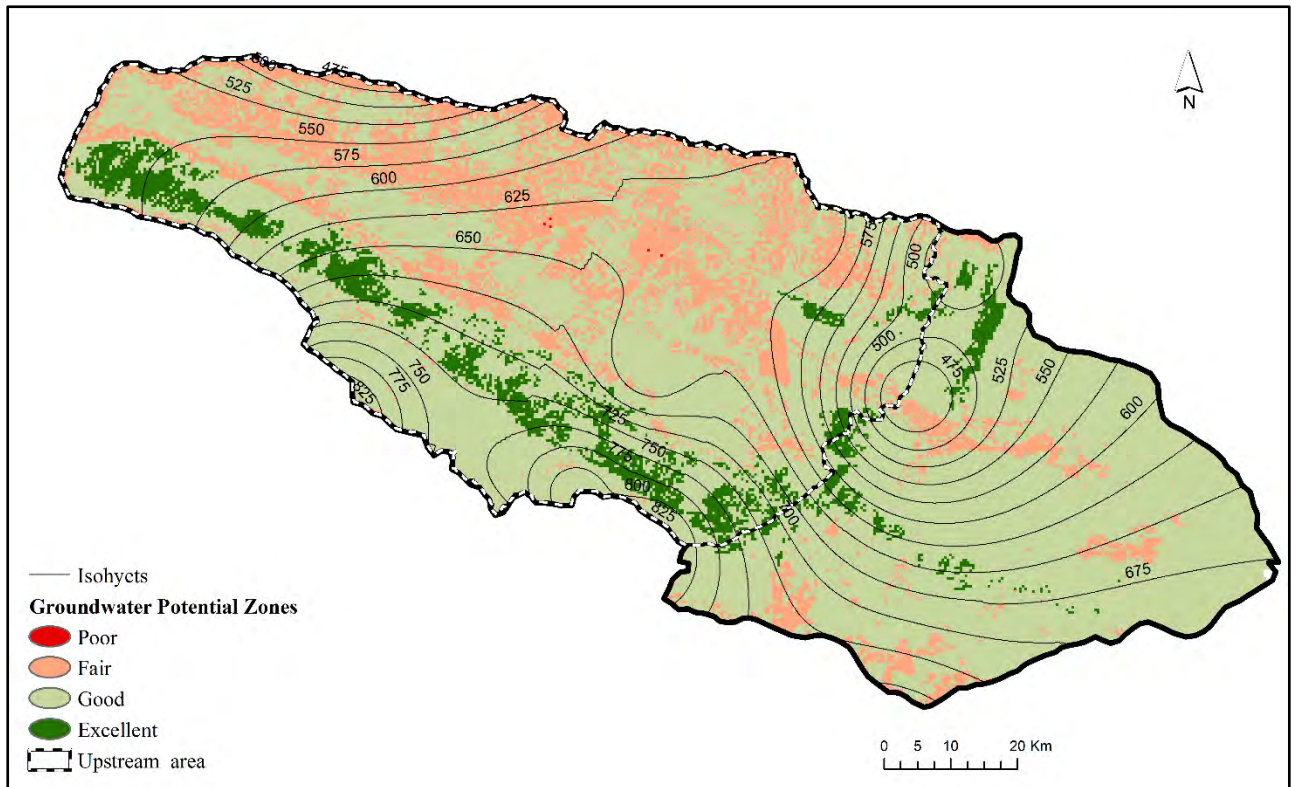


Figure 5.4. Map drawn in ArcGIS showing demarcated groundwater potential zones overlaid with isohyets (Isohyets-lines depicting areas with same rainfall amount)

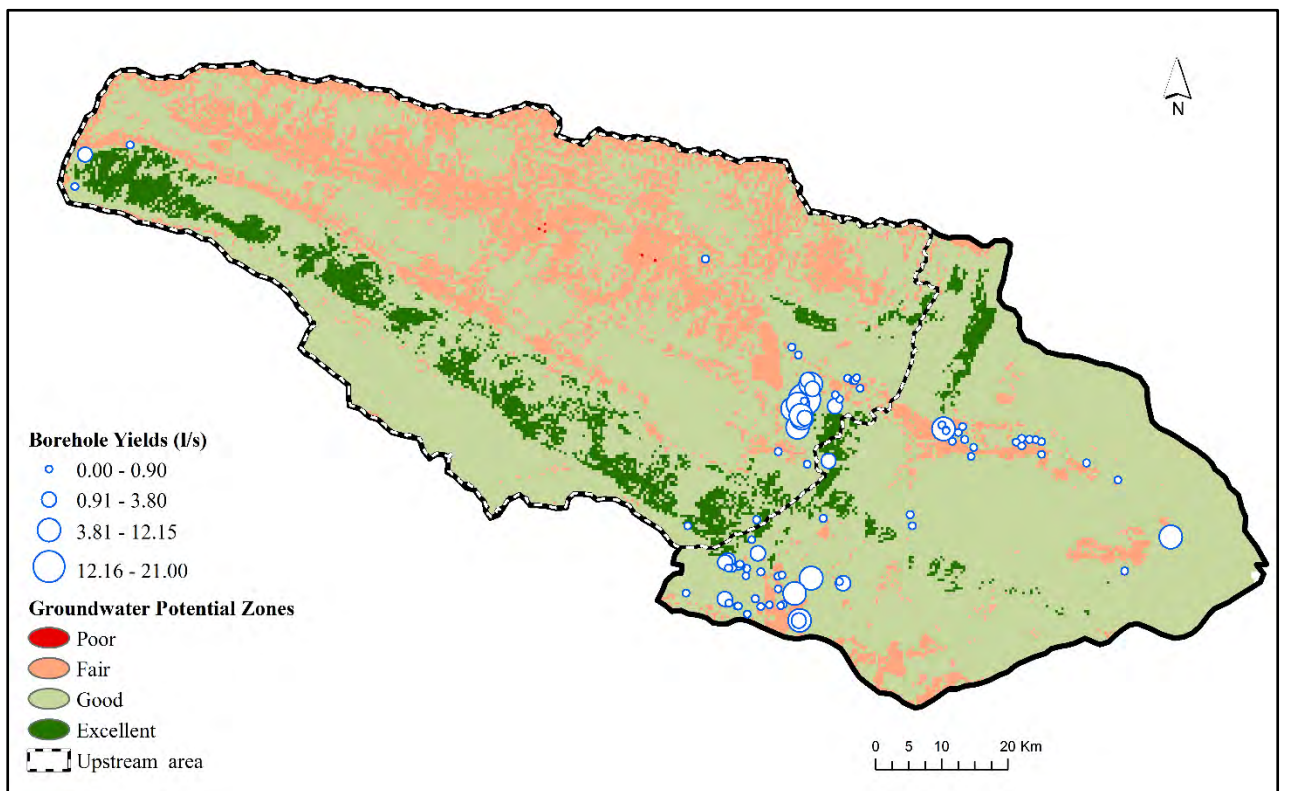


Figure 5.5. Map drawn in ArcGIS showing demarcated groundwater potential zones with superimposed boreholes and wells

5.1.4 The developed conceptual-perceptual model

The probable conceptual-perceptual model was developed from the integration of geological structures and groundwater flow using cross-sections (AA') for upstream area and (CC') to represent the downstream area. The model (Figure 5.6) indicates that the upstream area is dominated by irregularly folded and fractured TMG (Nardouw and Peninsula) rock outcrops which form the secondary aquifer with high pockets of surface runoff and groundwater flow paths in the Nardouw being perpendicular to the cross-section and controlled by the fault system.

The Bokkeveld group (aquitar) under cross-section (AA'), is in the syncline section with shale-bearing rocks that infill the Elands River valley providing substantial lateral recharge both through surface-channel seepage and surface percolation, a circumstance that accounts for Excellent groundwater potential (Figure 5.6). In the downward section (CC'), the TMG is overlaid by the aquiclude from the Uitenhage Group (primary aquifer) in the Swartkops River valley with both surface runoff and groundwater paths controlled by the fracturing and fault system that facilitate infiltration and forces subsurface flow horizontally downwards that comes out as artesian water in the downstream area (Figure 5.6) and this accounts for Excellent groundwater potential in the cross-section.

Results from the model indicate a lateral flow of groundwater is in a direction that coincides with flows on the surface within the UAB. Further investigation revealed that the underlying bedrock topography, syncline-anticline and fault system of the upstream area force subsurface flow downslope towards the location of established boreholes and other water collection points (Figure 5.6).

The steep mountainous areas with less fault systems were classified as Poor zones in terms of groundwater potential since they experience high surface runoff rates. Gently sloping areas were classified as Good groundwater potential areas, flat and valley areas as Excellent groundwater potential zones since they facilitate infiltration and lateral recharge both through surface-channel seepage and surface percolation.

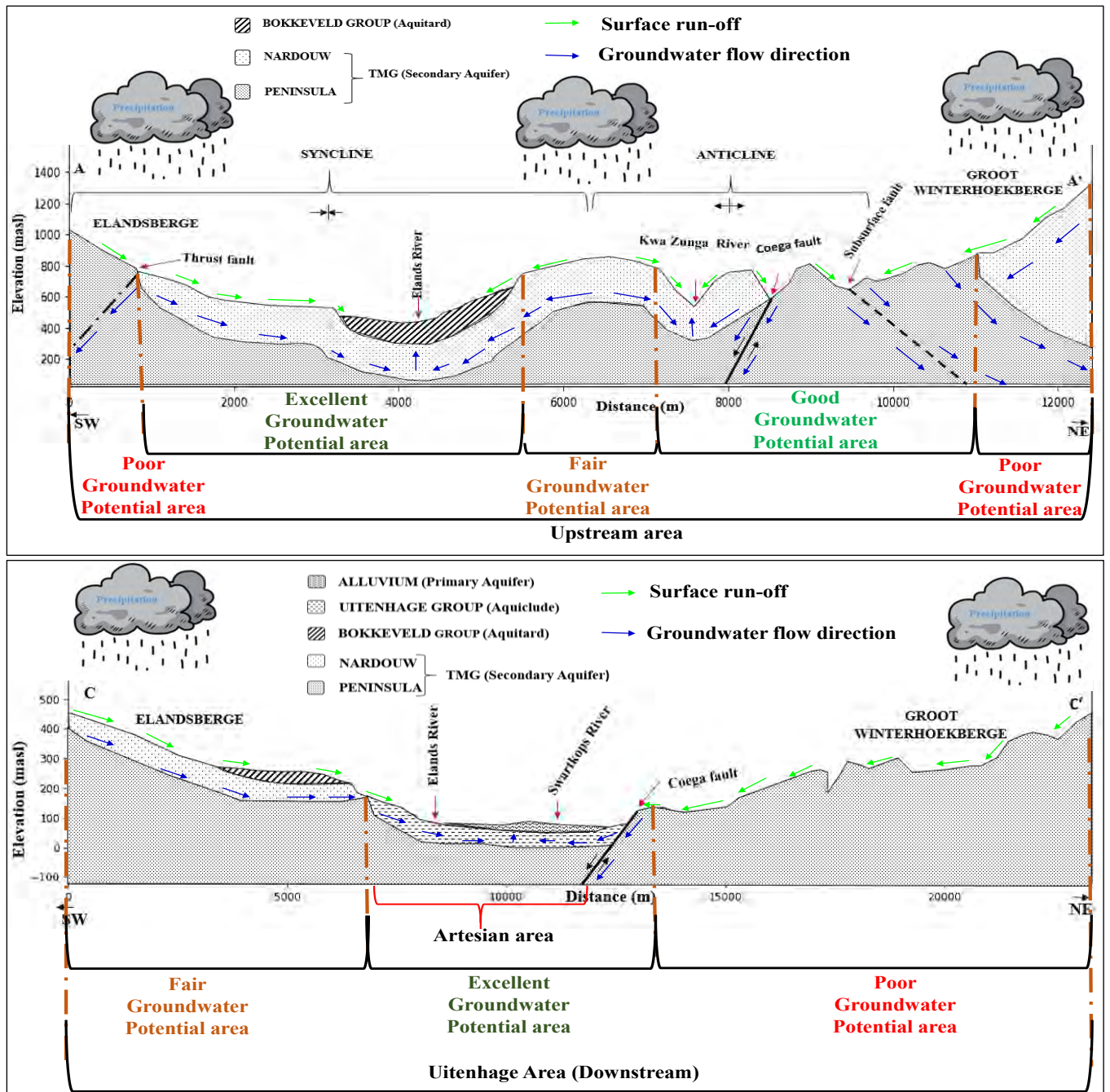


Figure 5.6. Cross-sections showing the developed conceptual-perceptual model illustrating groundwater recharge flow dynamics in the upstream area (AA') and downstream (CC')

5.2 Groundwater recharge estimation using Modified Pitman model

Single-run, of (IWR)-Rhodes University version of Pitman, as described in section 4.5.2 was used. The aim was to estimate recharge of upstream area given the model's inclusion of the more explicit groundwater routines (Hughes and Mazibuko, 2018; Tanner and Hughes, 2015). Here, various parameters (bold) (Table 5.4) were changed from their initial parameter sets (Table 4.13), and applied to the respective 19 sub-basins where the model's sensitivity to the parameter variations was internally accomplished by SPATSIM inbuilt tool (Hughes and Forsyth, 2006).

Table 5.4. Final model parameter set used at quaternary catchment scale

Parameters	M10A	M10B	M10C
RDF	1.280	1.280	1.280
AFOR	4.500	5.500	1.000
FF	1.400	1.400	1.400
PEVAP	1617.800	1622.400	1497.900
ZMIN	0.000	0.000	0.000
ZAVE	0.500	0.500	0.500
ZMAX	300.000	300.000	300.000
ST	85.000	85.000	85.000
FT	11.000	11.000	11.000
SL	0.000	0.000	0.000
POW	3.000	3.000	3.000
R	0.600	0.600	0.600
GW	35.000	35.000	35.000
GPOW	3.000	3.000	3.000
D.Dens	0.480	0.480	0.480
T	40.941	21.610	234.636
S	0.001	0.001	0.001
RWL	75.000	75.000	75.000
RSF	0.400	0.400	0.600

5.2.1 Pitman Hydrological Model performance

Figure 5.7 and Table 5.5 illustrate Pitman model flow performance in simulating discharge across the upstream area. It is observed that the model satisfactorily simulated the discharge during the calibration period with all the statistical performance measures (Table 5.5) being within acceptability threshold range (Table 4.11), however, a different situation was observed during the validation period where most of the statistical performance measures except Kling-Gupta Efficiency (KGE) were below acceptability threshold range.

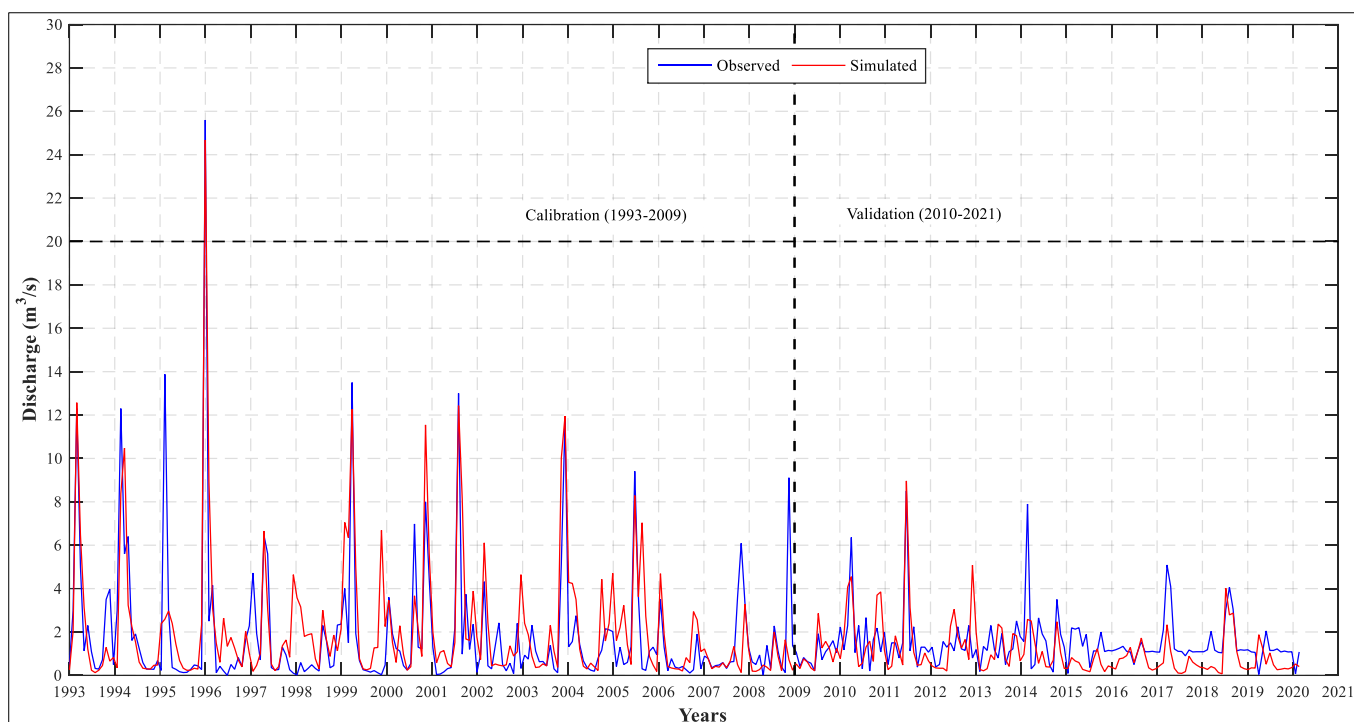


Figure 5.7. Pitman hydrography showing relationship between observed and simulated discharge

Table 5.5. Model flow performance measures

Objective function	Pitman		SWAT	
	Calibration	Validation	Calibration	Validation
<i>PBIAS</i>	20.3	29.1	19.8	16.8
R^2	0.63	0.43	0.52	0.51
<i>NSE</i>	0.58	0.33	0.51	0.41
<i>KGE</i>	0.71	0.50	0.57	0.67

The Flow Duration Curves (FDCs) are widely used characteristic signature of watersheds and are among the three most used graphical methods in hydrologic studies (Sadegh et al., 2016). They complement the cumulative distribution function of streamflow where the discharge is plotted against exceedance probability and shows the percentage of time that a given flow rate is equaled or exceeded (Casper et al., 2012). This helps to provide probabilistic description of stream flow at a given location.

The results presented in Figure 5.8 display relatively significant differences between the observed and simulated flows during the calibration and validation periods. At intermediate and low flows, vivid mismatches were observed especially during the validation period, the simulated flows displayed were lower than the observed flows at low flow section.

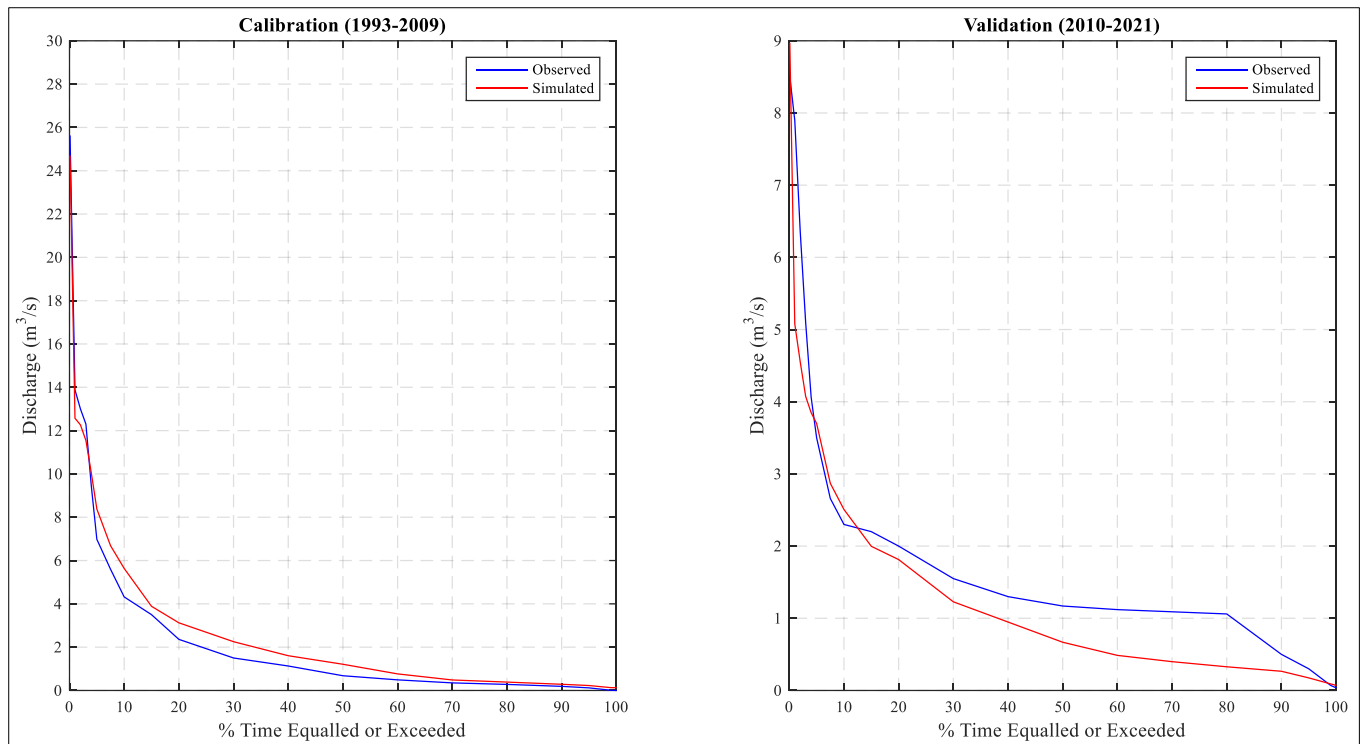


Figure 5.8. Pitman flow duration curves showing relationship between observed and simulated discharge

5.2.2 Pitman Hydrological Model recharge results

Using Mann-Kendall statistical test (MK), the Pitman modelled groundwater recharge (Figure 5.9) in the upstream area that exhibited a decreasing trend throughout the study period (1993-2021) though the trend was statistically insignificant (p -value=0.323), when evaluated at the significance level of 5%. Model recharge output suggest that the highest annual groundwater recharge occurred during 2010-2011 (92.8 mm) and the lowest during 2018-2019 (63.3 mm) (Table 5.6 and Figure 5.9).

Furthermore, the Pitman model replicated low recharge values expected in drought events in terms of low rainfall (i.e., 2007/2008; 2015/2016; 2016/2017 and 2018/ 2019) as was reported in the literature by: South African scholars such as Archer, 2019; Graw et al., 2017; Hughes, 2019b; Ngaka, 2012; Nolte et al., 2021 and Slaughter et al., 2011.

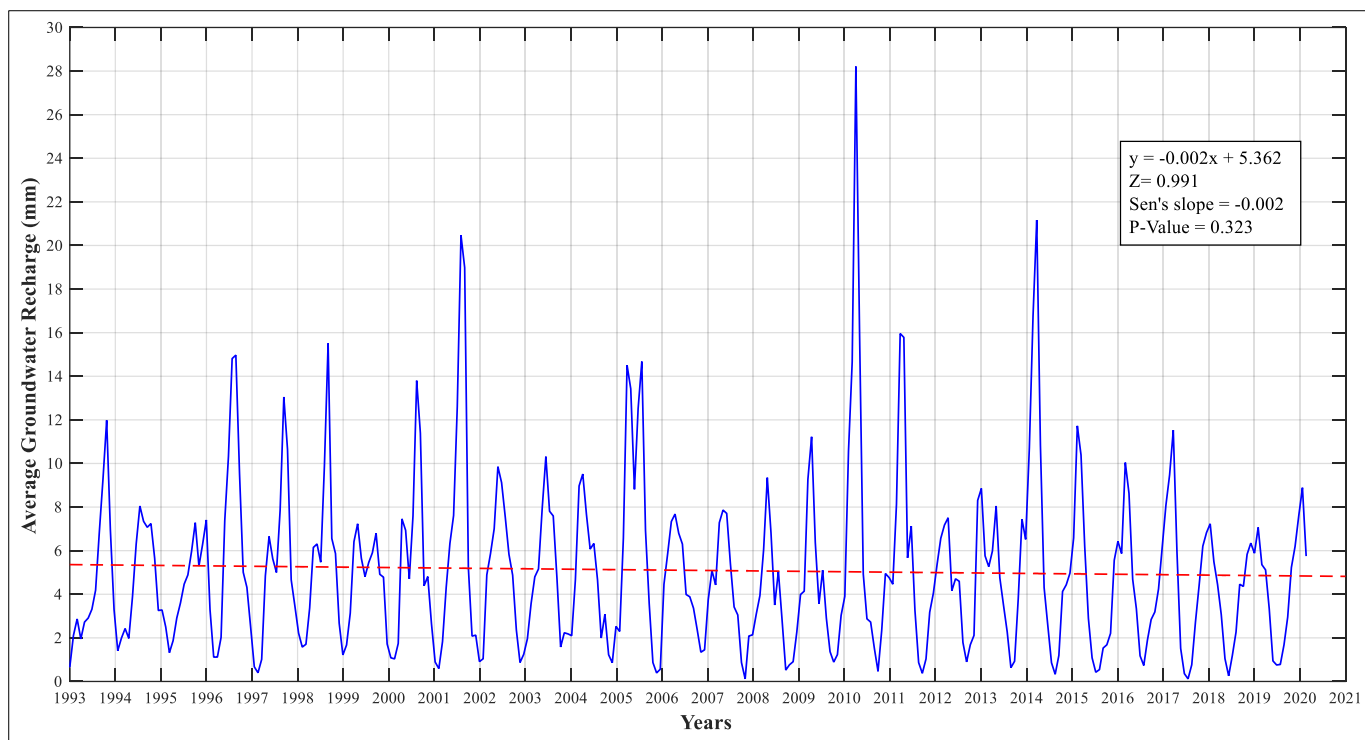


Figure 5.9. Pitman hydrography of estimated groundwater recharge

Pitman model simulated annual surface runoff that ranged between 20.4 mm to 249.7 mm with the mean annual value of about 98.1 mm^{-1} (Tables 5.6 and 5.7). The lowest surface runoff value (20.4 mm) simulated was observed in 2018-2019 hydrological year.

Table 5.6. Mean annual estimated Pitman groundwater recharge and surface runoff for upstream area

Year	Recharge (mm)	Surface runoff (mm)	Year	Recharge (mm)	Surface runoff (mm)	Year	Recharge (mm)	Surface runoff (mm)
1993-1994	55.8	134.7	2004-2005	60.7	154.4	2015-2016	57.7	46.2
1994-1995	56.8	147.1	2005-2006	82.5	155.8	2016-2017	46.9	28.3
1995-1996	46.6	64.0	2006-2007	54.7	89.1	2017-2018	57.3	61.8
1996-1997	83.3	249.7	2007-2008	53.9	79.7	2018-2019	46.0	20.4
1997-1998	62.6	79.2	2008-2009	44.4	40.1	2019-2020	47.1	59.6
1998-1999	66.9	96.6	2009-2010	50.9	43.8	2020-2021	49.2	36.5
1999-2000	56.8	146.6	2010-2011	92.8	107.0			
2000-2001	67.2	123.2	2011-2012	69.7	85.3			
2001-2002	85.5	202.5	2012-2013	50.7	85.3			
2002-2003	61.5	84.4	2013-2014	58	96.3			
2003-2004	58.5	66.4	2014-2015	89.3	99.7			

Table 5.7. Average quaternary catchment water balance components of the upstream area generated using the Modified Pitman model

Parameters	M10A (mm)	M10B (mm)	M10C (mm)
Rainfall (MAP)	691.1	717.9	700.0
Actual Evapotranspiration	518.2	542.7	514.2
Soil moisture store	429.0	437.1	439.0
Surface runoff	95.6	90.7	108.0
Soil moisture runoff	18.7	20.4	18.9
Recharge	59.3	64.8	59.6
Groundwater runoff	41.6	39.5	0.5

As shown in Figure 5.10, greater average soil moisture storage was predicted in lower sections of upstream area and syncline parts of Elands River valley, which are known for their irrigated agricultural activities (Maclear, 2001). Surface runoff generation (Figure 5.11) was predicted to be highest in the middle and downstream sections, higher baseflow and soil moisture runoff values (Figure 5.11) were generated and observed in highly fractured and faulted sections of the upstream area.

Generally, groundwater recharge generated was predicted to be higher in the central and downstream areas of the study area that have high structural fracturedness, syncline features and valley floor spots. This conforms to results from the conceptual-perceptual model (Figure 5.6) and those from previous studies of Bailey et al., 2016 and Maclear, 2001.

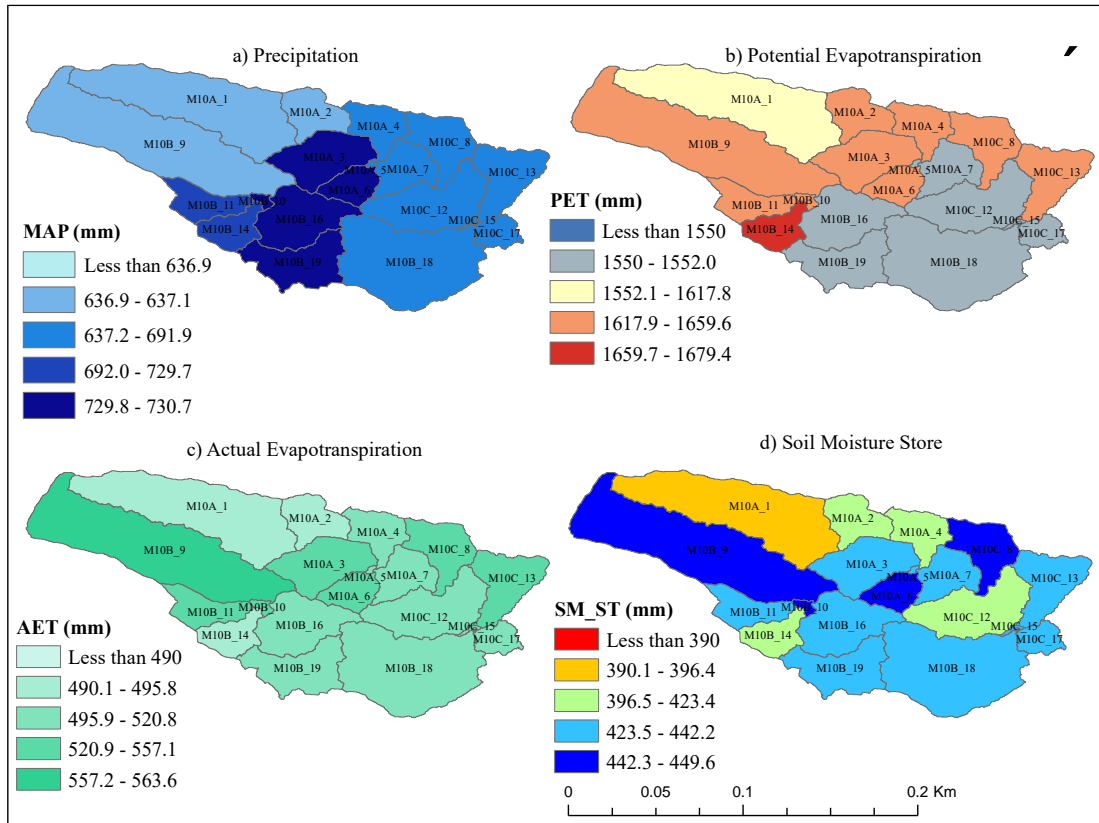


Figure 5.10. Map drawn in ArcGIS showing spatial distribution of MAP, PET, AET and SM_ST for the study area

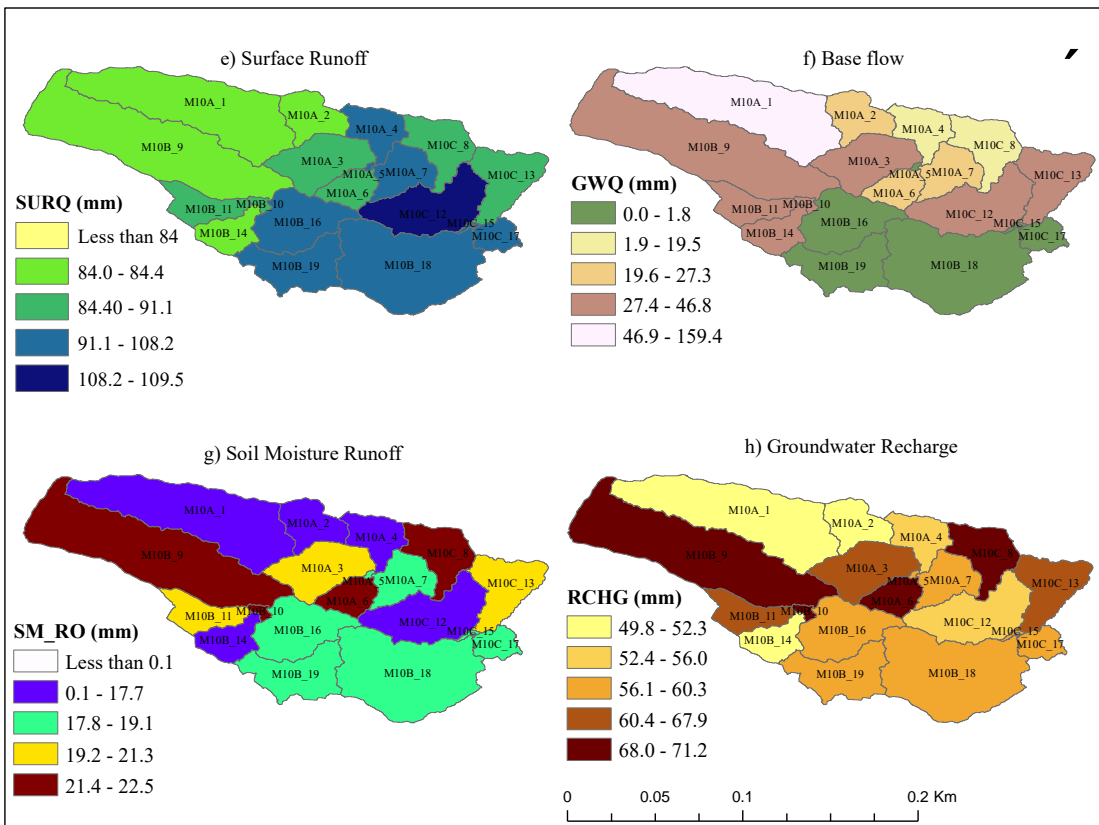


Figure 5.11. Map drawn in ArcGIS showing spatial distribution of SURQ, GWQ, SM_RO and RCHG for the study area

5.3 Groundwater recharge estimation using SWAT model

Here, parameters presented in Table 5.8 and Table 5.9 which are key for groundwater recharge were assessed and evaluated. To limit the number of variables that are allowed to vary in the calibration process at least in some of the iterations, sensitivity analysis was done on the parameters, ranked, and bolded with their respective t-statistic values according to the level of sensitivity (Tables 5.8 and 5.9).

It is observed from Table 5.8 that the most sensitive parameter during calibration is maximum canopy storage, followed by saturated hydraulic conductivity and the least being soil evaporation compensation factor, however, during the validation period, Saturated hydraulic conductivity parameter was the most sensitive, followed by maximum canopy and the least still being soil evaporation compensation factor.

Table 5.8. Sensitivity of parameters during calibration of SWAT-CUP

#Parameter Name	Description	Rank	t-Stat	P-Value
A_CANMX.hru	Maximum canopy storage	1	15.870	5.99E-4
R_SOL_K.sol	Saturated hydraulic conductivity ($\mu\text{m/s}$)	2	-2.663	0.008
V_REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur (mm)	3	-1.760	0.077
R_SLSUBBSN.hru	Average slope length	4	1.613	0.107
A_GW_DELAY.gw	Groundwater delay (days)	5	1.356	0.176
R_ALPHA_BF.gw	Base flow alpha factor (days)	6	1.299	0.195
A_RCHRG_DP.gw	Deep aquifer percolation fraction	7	-1.261	0.208
A_GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur (mm)	8	0.987	0.324
R_SOL_Z.sol	Depth from soil surface to bottom layer	9	-0.893	0.372
R_SOL_BD.sol	Moist bulk density (g/mL)	10	-0.765	0.445
A_GW_REVAP.gw	Groundwater revap coefficient	11	-0.637	0.524
A_EPCO.hru	Plant uptake compensation factor	12	0.464	0.643
A_SURLAG.bsn	Surface runoff lag time	13	-0.387	0.700
R_CN2.mgt	Run off curve number (mm)	14	0.364	0.716
R_SOL_AWC.sol	Available water capacity of the soil layer	15	-0.150	0.881
A_ESCO.hru	Soil evaporation compensation factor	16	-0.074	0.941

Table 5.9. Sensitivity of parameters during validation of SWAT-CUP

#Parameter Name	Description	Rank	t-Stat	P-Value
R_SOL_K.sol	Saturated hydraulic conductivity ($\mu\text{m/s}$)	1	-6.132	1.80E-9
A_CANMX.hru	Maximum canopy storage	2	14.738	0.000
R_SLSUBBSN.hru	Average slope length	3	2.040	0.042
R_ALPHA_BF.gw	Base flow alpha factor (days)	4	1.887	0.060
V_REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur (mm)	5	-1.362	0.174
A_GW_DELAY.gw	Groundwater delay (days)	6	1.305	0.192
A_RCHRG_DP.gw	Deep aquifer percolation fraction	7	-1.013	0.311
R_SOL_BD.sol	Moist bulk density (g/mL)	8	-1.037	0.300
R_SOL_Z.sol	Depth from soil surface to bottom layer	9	0.719	0.472
A_GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur (mm)	10	0.711	0.478
R_SOL_AWC.sol	Available water capacity of the soil layer	11	-0.648	0.517
A_SURLAG.bsn	Surface runoff lag time	12	-0.611	0.541
A_GW_REVAP.gw	Groundwater revap coefficient	13	-0.399	0.690
A_EPCO.hru	Plant uptake compensation factor	14	0.248	0.804
R_CN2.mgt	Run off curve number (mm)	15	-0.152	0.879
A_ESCO.hru	Soil evaporation compensation factor	16	0.045	0.964

5.3.1 SWAT Hydrological Model performance

Figure 5.12 and Table 5.5 illustrate SWAT model performance in simulating discharge across the upstream area. It is observed that the model satisfactorily simulated the discharge during both the calibration and validation periods with majority of the statistical performance measures except NSE in validation period (Table 5.5) being within acceptability threshold range (Table 4.11).

The results presented in Figure 5.13 display significant differences between the observed and SWAT simulated flows during the calibration and validation periods. At both intermediate and low flows, significant mismatches between observed and simulated flows were observed in the low flow section especially during the validation period and the simulated flows displayed to be lower than the observed flows.

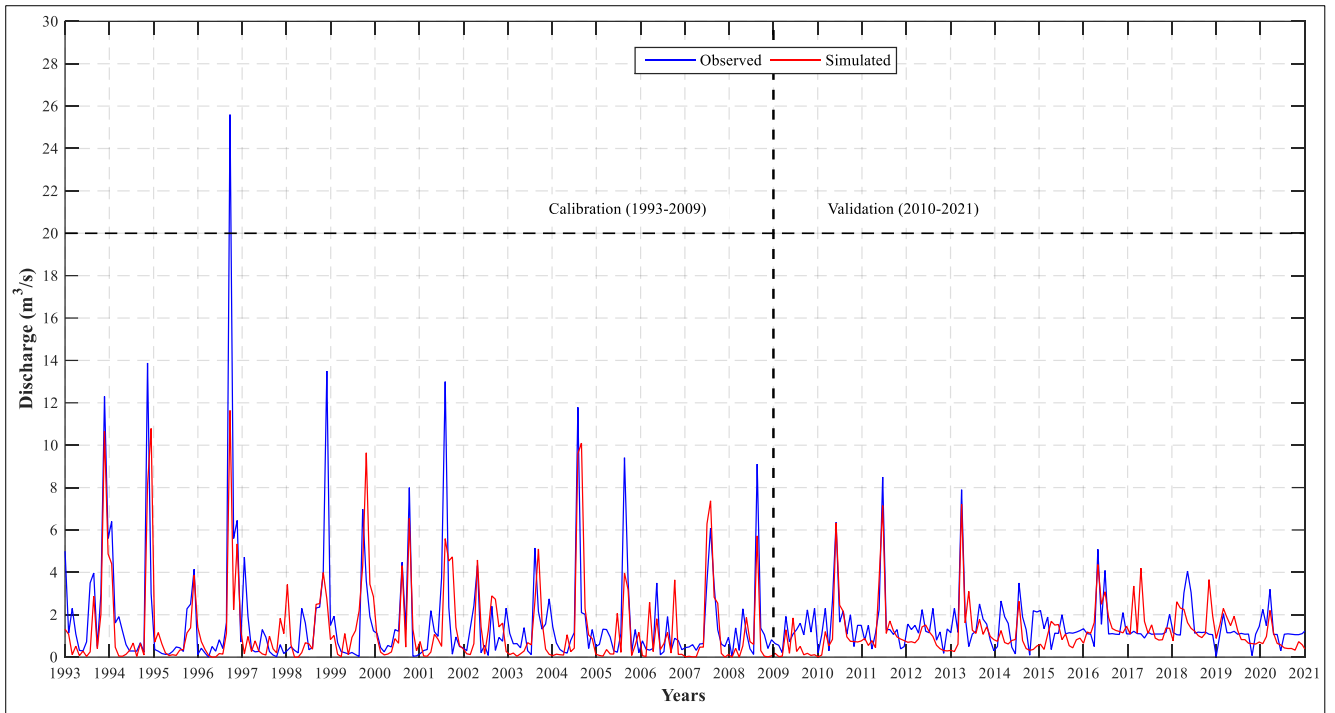


Figure 5.12. SWAT hydrograph showing relationship between observed and simulated discharge

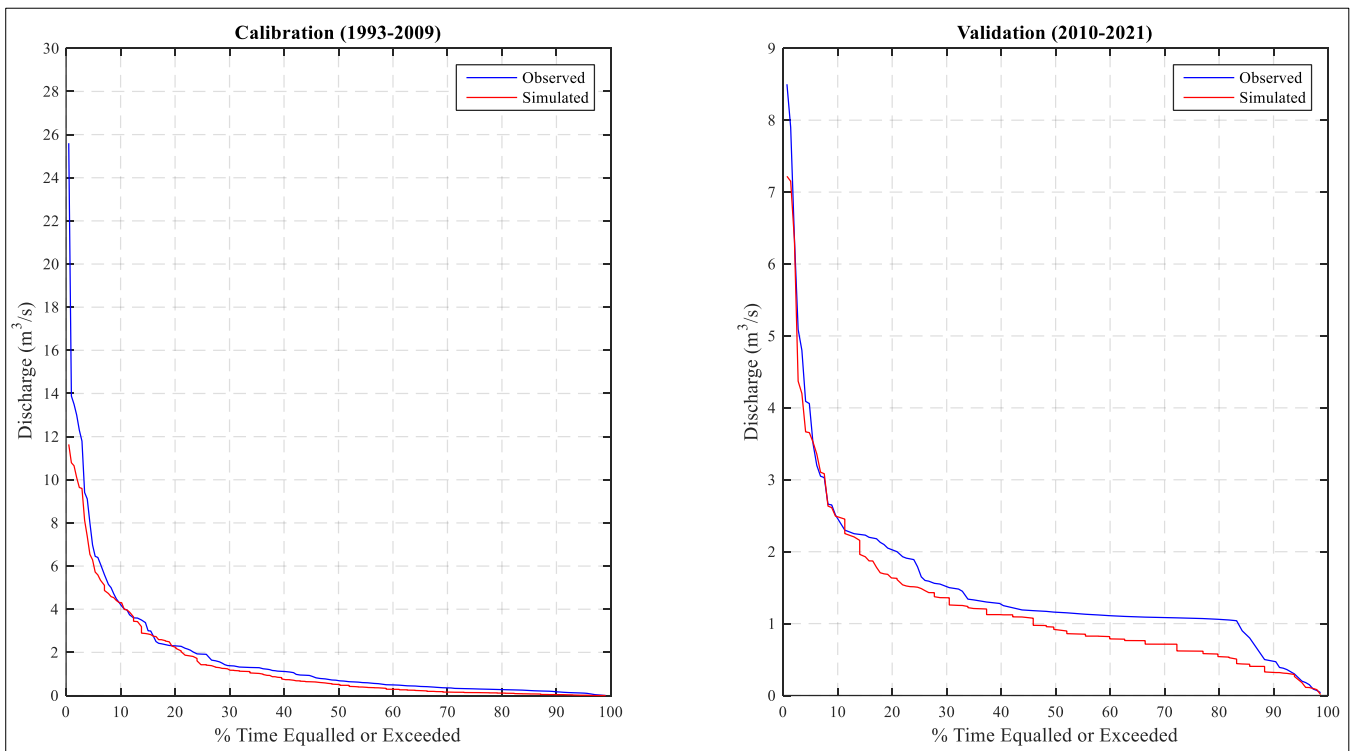


Figure 5.13. SWAT Flow duration curves showing relationship between observed and simulated discharge

5.3.2 SWAT Hydrological Model recharge results

Mann-Kendall statistical test results depicted a decreasing trend, in the SWAT modelled groundwater recharge throughout the study period (1993-2021), with a statistically significant trend ($p\text{-value}=1.564 \times 10^{-5}$) when evaluated at the significance level of 5% (Figure 5.14). The model predicted that the highest annual groundwater recharge occurred during the 1996-1997 hydrological year (182.8 mm) and the lowest value was estimated during the 2020-2021 hydrological year (14.4 mm) (Table 5.10 and Figure 5.14).

Like the Pitman model, the SWAT model simulated low recharge values as expected to occur in the reported drought events (i.e., 2007/2008; 2015/2016; 2016/2017 and 2018/ 2019) with low rainfall. SWAT simulated annual surface runoff that ranged between 7.9 mm to 185.6 mm with the mean annual value of about 96.8mm^{-1} (Tables 5.10 and 5.11). Like Pitman modelled surface runoff, the lowest surface runoff value modelled by SWAT (7.9 mm) was also observed in 2018-2019 hydrological year.

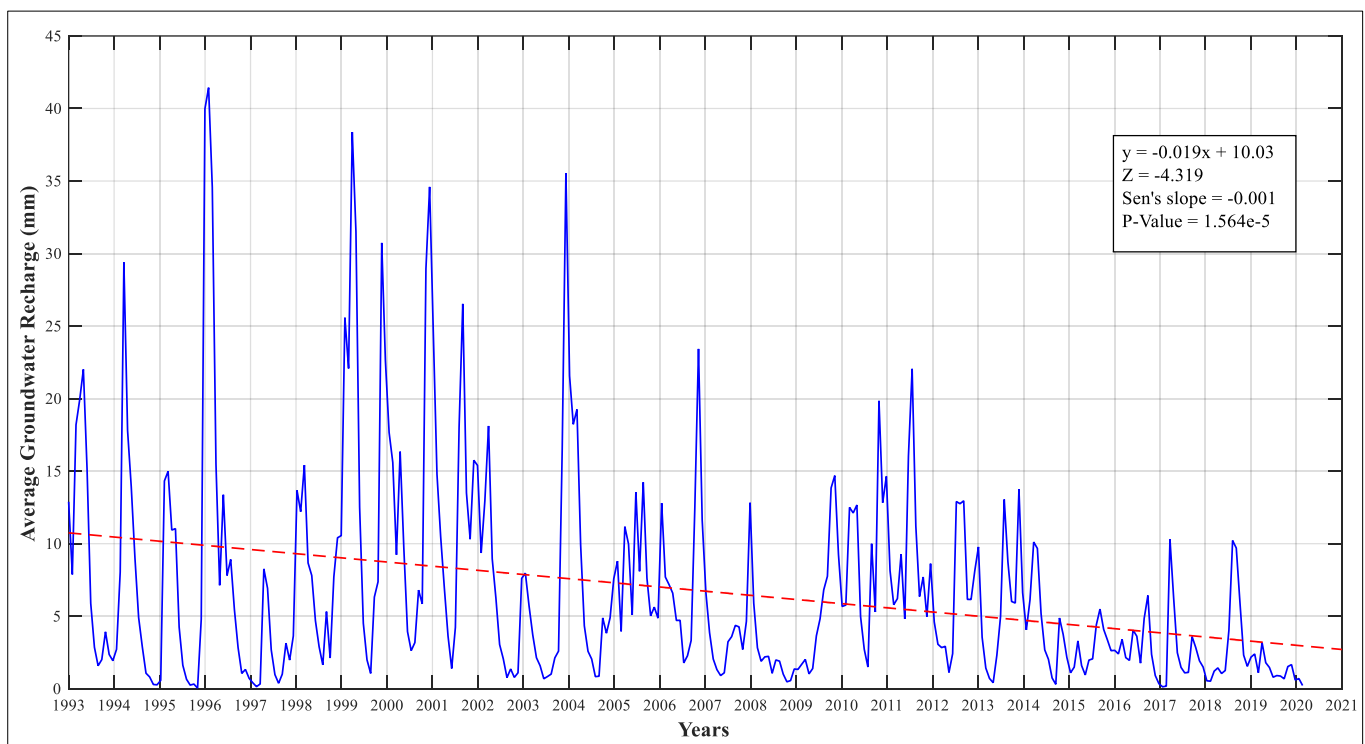


Figure 5.14. SWAT hydrography of estimated groundwater recharge

Table 5.10. Mean annual estimated SWAT groundwater recharge and surface runoff for upstream area

Year	Recharge (mm)	Surface runoff (mm)	Year	Recharge (mm)	Surface runoff (mm)	Year	Recharge (mm)	Surface runoff (mm)
1993-1994	114.7	107.4	2004-2005	135.6	107.1	2015-2016	29.2	33.8
1994-1995	92.8	135.3	2005-2006	82.7	96.2	2016-2017	35.6	14.6
1995-1996	59.3	41.5	2006-2007	82.8	85.7	2017-2018	36.9	53.0
1996-1997	182.8	185.6	2007-2008	72.3	55.0	2018-2019	24.6	7.9
1997-1998	26.3	66.6	2008-2009	48.5	16.1	2019-2020	43.2	24.4
1998-1999	80.1	79.8	2009-2010	18.4	18.1	2020-2021	14.4	13.3
1999-2000	172.6	94.7	2010-2011	110.9	92.2			
2000-2001	145.8	113.7	2011-2012	101.1	86.7			
2001-2002	180	160.3	2012-2013	91.5	51.1			
2002-2003	116.5	69.7	2013-2014	77.3	74.2			
2003-2004	34.5	37.8	2014-2015	91.4	84.2			

Table 5.11. Average quaternary catchment water balance components generated using SWAT model

Parameters	M10A (mm)	M10B (mm)	M10C (mm)
Rainfall (MAP)	691.1	717.9	700.0
Actual Evapotranspiration	500.3	560.7	483.4
Lateral flow	53.0	19.3	15.0
Surface runoff	73.7	60.9	84.7
Water yield	165.0	127.4	186.2
Recharge	53.0	69.2	124.7
Groundwater runoff	35.4	43.8	55.4

As shown in spatial distribution maps (Figures 5.15 and 5.16), SWAT model results indicated that the downstream section of the study area was predicted to experience the highest surface runoff, with moderate values in the middle section. The highest values of lateral flow were predicted mostly in the middle section, whereas generally, higher groundwater runoff (Baseflow), groundwater recharge, deep aquifer recharge, and water yield (WYLD) values were predicted for the downstream section and with lower values in middle and upper-most section.

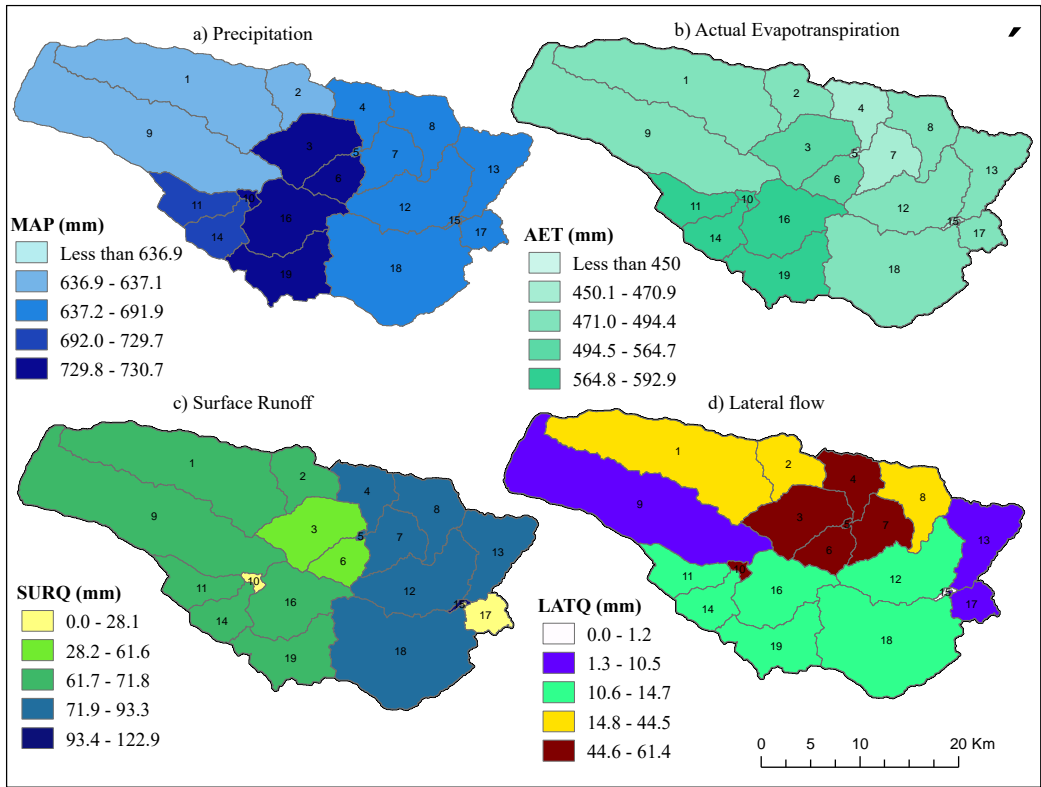


Figure 5.15. Map drawn in ArcGIS showing spatial distribution of MAP, AET, SURFQ and LATQ

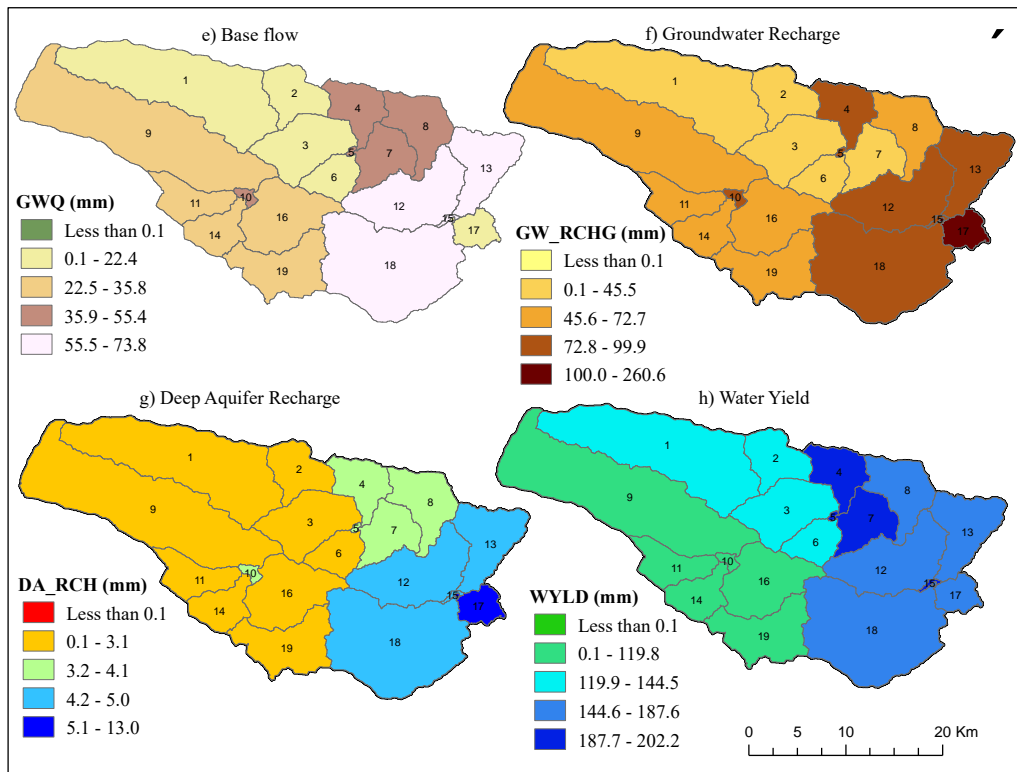


Figure 5.16. Map drawn in ArcGIS showing spatial distribution of GWQ, GW_RCHG, DA_RCH and WYLD

5.4 Assessing the value of application of the two hydrological models

5.4.1 Pitman and SWAT model comparison

The models satisfactorily captured the natural catchment behaviour of the upstream area since the statistical performance measures were within the acceptability threshold ranges (Table 4.11). The Pitman simulated flows were more variable compared to the flows simulated by SWAT. Based on percentile, the Pitman model over-predicted flows during the 5th, 75th, and 95th percentiles whereas the SWAT model under-predicted flows throughout all the percentiles (Table 5.12).

Concerning performance measures (Table 5.12), the Pitman outperformed the SWAT model during the calibration period and underperformed during the validation period. The SWAT model simulated well at the calibration phase compared to the validation phase. From Figure 5.17, it can be deduced that the two models slightly simulated similar streamflow values that were in the same pattern with the rainfall.

Table 5.12. Statistics for observed and simulated streamflow (10-1993 to 09-2021) at watershed outlet

Statistical Index	Observed (mm)	Pitman (mm)		SWAT (mm)	
Mean	1.800	1.731		1.368	
% difference		-3.833		-24.00	
Minimum	0.000	0.072		0.000	
Maximum	25.6	24.678		11.640	
Standard deviation	3.064	2.511		1.867	
Coefficient of variance	1.703	1.451		1.364	
5 th percentile	0.137	0.216		0.040	
25 th percentile	0.455	0.394		0.290	
50 th percentile	1.110	0.873		0.781	
75 th percentile	1.910	1.999		1.497	
95 th percentile	6.171	6.534		4.939	
		Calibration	Validation	Calibration	Validation
R^2		0.63	0.43	0.52	0.51
NSE		0.58	0.33	0.51	0.41
$PBIAS$		20.3	29.1	19.8	16.8
KGE		0.71	0.50	0.57	0.67

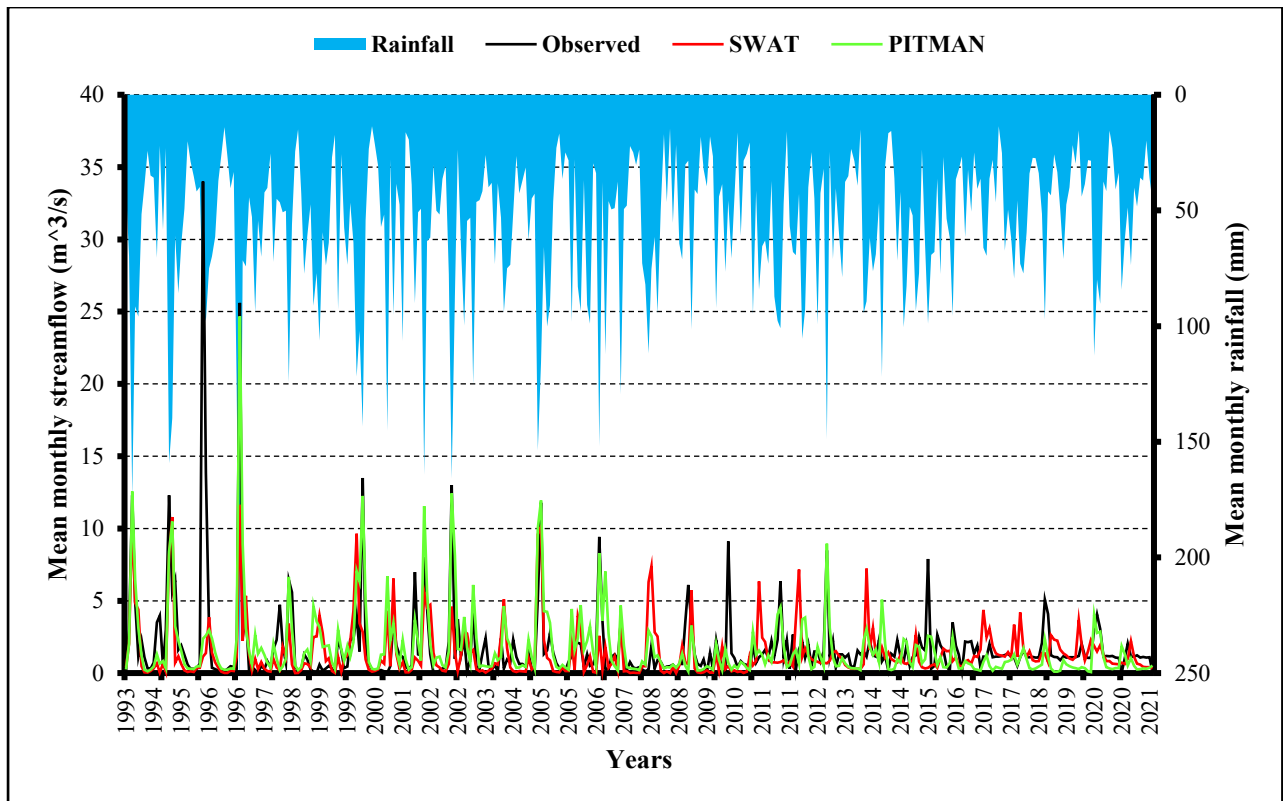


Figure 5.17. Rainfall, observed and simulated monthly streamflow estimated using Modified Pitman and SWAT models during calibration and validation phases

5.4.2 Comparison with national scale studies: Groundwater Recharge Assessment II and the Water Resources 2012

When the simulated annual recharge values were compared on a quaternary catchment basis with Groundwater Recharge Assessment II (GRAII) (Table 5.13), the two models simulated annual recharge that compared reasonably well with the GRAII values in quaternary catchments of M10A and M10B, with differences in the means of less than 20%. In M10C, both models simulated recharge values that were notably different to GRAII and to one another, with differences in means of -30% to 50% compared to the GRA II estimate, however, it must be noted that GRAII estimates were coarsely modelled.

In comparison with annual runoff modelled at the regional scale for the South African Water Resources study, WR2012, (Bailey et al.,2016), (Table 5.14 and Figure 4.1), SWAT predicted more similar mean runoffs to WR2012 for M10A and M10C than Pitman, while Pitman’s mean runoff for M10B was more such as WR2012 than SWAT. Generally, all the two models predicted much more interannual quaternary variability in runoff than that modelled by WR2012.

In a review of previous studies in the TMG areas (Table 3.1), they locally estimated percentages of groundwater recharge though using different periods and methods, their results are somewhat close to those simulated by both Pitman and SWAT models for the upstream area and thus suggesting that the application of both Pitman and SWAT models can provide satisfactory estimates of groundwater recharge in the upstream area.

Table 5.13. Comparison of regional annual recharge with simulated annual recharge from Modified Pitman and SWAT models

Quaternary catchment	Annual Recharge (mm/yr), means and ranges			% difference in mean vs GRAII	
	Observed Groundwater Recharge Assessment 2 (GRAII)	Pitman	SWAT	Pitman	SWAT
M10A	67.9	59.3 (42.7-91.9)	60.6 (3.2-159.9)	-12.7	-10.8
M10B	80.1	64.4 (49.6-92.7)	70.5 (9.2-189.7)	-19.6	-12.0
M10C	85	59.3 (39.2-94.2)	128.9 (25.5-287)	-30.2	51.6

Table 5.14. Comparison of annual runoff modelled for the national WR2012 study with simulated runoff from Modified Pitman and SWAT models

Quaternary catchment	Annual Runoff (mm/yr), means and ranges			% difference in mean vs WR2012	
	WR2012 (Bailey ,A.K, and Pitman, 2016)	Pitman	SWAT	Pitman	SWAT
M10A	75 (50-100)	94.7 (19.5-243.5)	73.4 (6.5-189.3)	26.3	-2.1
M10B	75 (50-100)	89.1 (25.4-239.6)	60.1 (11.6-243.5)	18.8	-19.9
M10C	75 (50-100)	106.9 (14.7-272.5)	85.4 (4.5-216.6)	42.5	13.9

CHAPTER SIX

DISCUSSION OF RESULTS

Although there have been several studies in the TMG areas of South Africa which have assessed aquifer characteristics such as recharge, accurate measurement of groundwater recharge is still a difficult task largely due to these areas being characterized by highly folded and fractured structures with highly heterogeneous recharge volumes and deep groundwater flows. Additionally, many recharge estimation methods do not consider the high variability of recharge at local scales, largely due to the difficulty of estimating recharge which occurs through preferential flow paths. The variety of recharge studies are however useful, as due to the high heterogeneity of recharge, it is recommended to use several methods (both local and intermediate scale) for recharge estimation (Leketa et al.,2019; Watson et al.,2020; Wu, 2005; Xu et al.,2018).

Although the greater understanding of groundwater dynamics (particularly recharge) in the TMG are useful, localized differences in climate particularly seasonality will impact recharge amounts in specific regions, thus, a need for modelling to assist in understanding these influences. Models can provide a time series of recharge using local climate data together with the ability to incorporate a variety of factors and processes governing recharge.

A key element of catchment systems is the understanding and evolution of drainage patterns. Savenije et al. (2017) detail drainage patterns for the surface (infiltration over the land surface with minimal erosion), for the unsaturated zone (the efficient replacement of moisture deficits and preferential drainage where there is excess moisture) and for the groundwater (the efficient and gradual drainage of groundwater). Savenije et al. (2017) argue that these patterns result in linear reservoir recession (at certain scales), which forms the basis of many simpler conceptual models. While a study of this type could certainly benefit from a more detailed numerical model, given time and resource constraints, setting up a detailed numerical model at the scale of the upper catchments of the UAB was not feasible.

Based on Savenije et al. (2017) assessment, models which are relatively simple and conceptually semi-distributed bear the potential to accommodate system features and their temporal evolution in a simple and efficient way. Conceptual models integrate natural heterogeneity within the system at larger modelling scales, and according to Savenije et al. (2017) can often represent drainage patterns better than detailed groundwater models. Based

on this assessment and the successful application of the Pitman and SWAT models in other similar studies (Abiye, 2016; Golmohammadi et al., 2014; Gymfi et al., 2017; Hughes et al., 2018, 2007; Jumbi et al., 2018; Leketa et al., 2019; Nolte et al., 2021), both models were selected to represent recharge dynamics of the upper catchments of the UAB.

In this study, a qualitative approach to integrate modelling with groundwater recharge dynamics was initially undertaken. Many recharge estimation methods demand a great deal of data, which are usually unavailable, which is the case in the UAB upper reaches. Given the lack of data and subsequent issue with model parameterization, the study developed a holistic conceptual-perceptual model which was instrumental in ensuring a conceptually appropriate set up that was achieved in both hydrological models (Modified Pitman and SWAT).

6.1 Conceptual-Perceptual model for groundwater recharge dynamics

The developed conceptual-perceptual model indicated that the geological nature of the upstream area is characterised by the highly fractured TMG. The highly fractured exposures found in the upstream area (similar to TMG all across the Cape fold belt, Xu et al., 2018) are localized zones of recharge with preferential flow characteristics which are responsible for the movement of deep groundwater downstream which is eventually overlain by the aquitard of the Uitenhage group (geological formation, Figures 4.4 and 4.5). This is the reason for the artesian conditions observed in the downstream area of UAB. The UAB is primarily recharged from groundwater flow emanating from the mountainous areas of the upstream area as was reported by studies of Baron (2000), Maclear (2001) and Nyawo (2017).

Drawn groundwater level contour maps (Figures 5.3 (c and d)) represent the northwest-southeast flow paths as the general directional flow of surface and subsurface water following the topographic gradient from the mountainous upstream area towards the flatter downstream area. This is characteristic of TMG regions, many of which are described by De Vries and Simmers, 2002; Mkali, 2020; Wu, 2005 and Xu et al., 2009 in other TMG areas within South Africa. It was found that areas with Good to Excellent groundwater potential zones are highly fractured zones. Furthermore, the study area has a series of major fault systems, in particular the Coega fault (oriented northwest to southeast towards the sea), which is thought to divide UAB into two separate systems that are hydrogeologically independent of each other. The Coega fault is thought to act as a tensional fault with a vertical southward displacement of

sediments (Maclear, 2001). However, little is known on whether it is a preferential flow path for the TMG water movement beneath the Uitenhage geological group.

The Eland River valley sits in a syncline dominated by the Bokkeveld geology group (along the valley floor) with Nardouw TMG rock outcropping at the margins (Figure 5.1). These formations cause localized differences in recharge within the TMG region as they don't feed the floodplain and alluvium aquifers directly, but rather the valley bottom aquifers are supplemented by mountain tributary streams that bring inflows from the Peninsula rock outcrops higher up in the mountains (Figure 5.2). Therefore, recharge controls in this area are linked to climate, geology, and topography, all of which exhibit high spatial variability in the study region.

6.2 The estimation of groundwater recharge dynamics within the Modified Pitman model

The modified Pitman Model incorporates more explicit groundwater recharge and discharge routines (Hughes, 2004), which means the model is able to simulate the interactions between surface water and groundwater. In terms of recharge, the Modified Pitman model contains four key parameters (ST, SL, GW and GPOW; see Table 2.2). The model calculates recharge using a non-linear function of the soil storage (which also represents the unsaturated zone) and a maximum monthly recharge parameter. Groundwater inflow from upstream sub-catchments also adds to downstream groundwater storage volumes.

The choice for the usage of the Modified Pitman model lies in its simplicity to be set up with few input datasets, fewer parameters, and its ability to generate monthly variability of recharge as a time series for each sub-catchment. However, it is acknowledged that the recharge estimation routines are simple and many of the input parameters are conceptual and so based on regionalisation or local calibration.

The Pitman modelled groundwater recharge over the upstream area exhibited a decreasing statistically insignificant trend throughout the study period with the highest annual groundwater recharge estimated to be 92.8mm/year during the 2010-2011 period and the lowest estimate of 63.3 mm/year during the 2018-2019 period. It was also observed that the model replicated low recharge values at low rainfall periods during the drought years of (2007/2008; 2015/2016; 2016/2017 and 2018/ 2019). These low rainfall periods were reported in literature by South African scholars such as Archer, 2019; Graw et al., 2017; Hughes, 2019b; Ngaka,

2012; Nolte et al., 2021 and Slaughter et al., 2011. Generally, groundwater recharge generated, and other water balance parameters exhibited spatial and temporal variations across the study area which were consistent with expectations based on the conceptual-perceptual model and climatic variations.

6.3 Groundwater recharge dynamics estimation within the Modified SWAT model

SWAT model uses physical and empirical algorithms to estimate groundwater recharge by computing the water balance for each HRU in the model. The model can allocate the calculated recharge between both a shallow and deep aquifer at every HRU and its respective sub-basin based on the parameterization of an intermediate vadose zone.

SWAT was chosen for this study due to its ability to make use of spatiotemporal input datasets such as topography (DEM), land cover, and soil to discretize an area under study into various internally homogeneous units (HRUs), which provides an increased level of detail arguably necessary for understanding groundwater dynamics in a complex area like upstream area of UAB. The model is also open source and can run through Geographical Information System (GIS) interfaces, which have demonstrated attractive features for users. However, the model is data intensive, and requires a longer learning curve, for one to use it.

The SWAT modelled groundwater recharge over the study area displayed a decreasing statistically significant trend throughout the study period with the highest annual groundwater recharge estimated to be 182.8mm/year during the 1996-1997 period and the lowest during 14.4 mm/year during the 2020-2021 period. The model also captured low recharge values that corresponded to the low rainfall amounts received. Generally, groundwater recharge generated, and other water balance parameters exhibited variable spatial and temporal variations across the study area. Compared with the Pitman model however, the model showed a higher degree of variability and responsiveness to climate.

6.4 Model assessment to estimate groundwater recharge

The natural hydrological catchment characteristics of the upstream area were satisfactorily captured by both the modified Pitman and SWAT models since their statistical performance measures were within the acceptability threshold ranges (Table 5.12) when compared with DWS flow gauges. The Pitman model estimated mean annual recharge was slightly lower compared to SWAT modelled recharge. Both model's recharge outputs were within the Groundwater Recharge Assessment II (GRAII), values for the various quaternary catchments.

Although GRAII estimates were coarsely modelled (Bailey et al., 2016), they still give an ideal starting point for comparison of the two-model output performances.

In a review of previous studies in the TMG areas of South Africa, the percentages of groundwater recharge estimated compared well to those estimated by both Pitman and SWAT models, thus suggesting that the application of both Pitman and SWAT models can provide satisfactory large scale estimates of groundwater recharge in TMG areas.

It should be noted, that although, there were closeness in the groundwater recharge values that were estimated by the two models, noticeable interannual change patterns of recharge (Figures 5.9 and 5.14), surface runoff and other water balance components with differing peaks and low values and timings were observed from the model outputs. In particular, there was much greater variability in monthly recharge simulated by the SWAT model. This scenario was attributed to a number of factors which are explained below.

The SWAT model requires soil, climate, DEM, and land use/ cover type as input (Abbaspour et al., 2015; Arnold et al., 2012) while modified Pitman basically input rainfall, PET and other parameters related to slope, land cover and soil which can be internally computed within its structure (Hughes et al., 2006; Tanner, 2013). Additionally, since the model is a physically based, semi-distributed model, and its inputs have a spatial-temporal component (Awan et al., 2014, 2013), thus, it is more detailed and able to represent complex heterogeneous catchment behaviour better.

The modified Pitman model uses average annual potential evapotranspiration values (PET) which are then distributed monthly across the study area, while SWAT model uses a timeseries of PET generated either on a daily or monthly time step using various PET methods (i.e., Penn-Monteith method). This is probably the most likely reason for the different outputs.

The Flow gauging station M1H012 (Swartkops River @ Uitenhage) is located downstream of the Groendal and Bulk River Dams, implying that the gauging station is under influence of the two dams which the model set-ups did not aim to represent. Rather the focus was on understanding the larger scale recharge dynamics. It is acknowledged that the flow data are only partly representative of the actual streamflow.

Given the short comings encountered in this study, it should be noted that the study increased understanding of the dynamics and volumes of recharge potentially supporting the aquifers of

the UAB. In addition, it seems a more detailed model is more appropriate to represent the highly heterogeneous region of the TMG. The study also demonstrated the value of using simpler (non physically based) models in studies of this nature where the data and/or resources are not available to support a more detailed numerical modelling exercise.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

The study showed various methods of understanding groundwater recharge and dynamics for the upstream area of Uitenhage Artesian Basin. These methods include conceptual-perceptual model development and the use of two hydrological models (Modified Pitman and SWAT). The conclusions drawn are presented below.

The probable qualitative conceptual-perceptual model that was developed depicted the dominance of irregularly folded and fractured TMG (Nardouw and Peninsula) rock outcrops coupled with fault systems in the upstream area that provide substantial lateral recharge both through surface-channel seepage and surface percolation. In the downward section, TMG is overlaid by the aquiclude from the Uitenhage Group with both surface runoff and groundwater paths controlled by the fracturing and fault system that forces subsurface flow horizontally downwards resulting into artesian conditions.

The two hydrological models (Pitman and SWAT), predicted decreasing rates of groundwater recharge in the upstream area over time, though they did predict average amounts and interannual patterns of recharge, surface runoff and other water balance components with differing peaks, low values and timings due to the difference input data and model structures. In reference to earlier findings within TMG areas, estimated percentages of groundwater recharge were close to those simulated by both Pitman and SWAT models and thus the application of both Pitman and SWAT models to estimate groundwater recharge in upstream area of UAB is satisfactory.

It was observed in the current study that in a TMG environment, processes normally dependent on local scales that are difficult to be described in complex ways and though a numerical model maybe reproducing well observed streamflow data, inherent problems associated in the modelling process may not be ignored, thus the need of a conceptual-perceptual understanding of such environments.

7.2 Recommendations

Estimating local and regional groundwater recharge is challenging due to the hydrogeological settings of TMG areas' complexity. A complicated recharge mechanism is produced by the

variations in rainfall over space, the scarcity of monitoring locations, the topography, and the geological settings of the upstream area. Consequently, the current study offers the following recommendations:

- Since the current study's low recharge rates are such those predicted for the TMG area, it is advised to exercise caution when developing a water supply strategy in these regions. The recharge rates within the pertinent recharging areas should be considered when designing and siting abstraction points such as boreholes. To avoid having a negative environmental impact, extraction volumes in each borehole or well should not exceed environmental recharge rates.
- Main requirement for estimating groundwater recharge is a sufficient collection of data, but needed datasets are typically not available at many locations, especially in remote study areas such as upstream area of UAB. Examples of these datasets include climate, water level data, streamflow, soil, vegetation, topography, and geology. Therefore, to fill the gaps in the available datasets in such circumstances, researchers should use remotely sensed data.
- For sustainable water resource management, future studies should concentrate on estimating groundwater use, abstraction rates and impacts of dams on groundwater recharge. It is likely that in medium to wet periods dams get full and overtopping and so don't impact streamflow that much, but during drier times they would reduce flows.
- One of the most crucial factors now considered while developing a qualitative conceptual-perceptual model is citizen science. When determining the contribution of artificial recharge in each area as well as human influence on landforms, soils, among others, knowledge from residents, such as irrigation patterns and volumes, is crucial. As a result, the study suggests that citizen science be used in future studies.
- The crop and vegetation information that the SWAT model uses was initially created under USA-specific conditions, one of the risks associated with applying the SWAT model to African circumstances is this, especially if the user wants to modify the database, however in the current study, it was overcome by using local literature and SOTERSAF dataset. This study recommends that more attention should be paid to the processes the model represents when employing any hydrological model in a TMG environment because those processes normally dependent on local scales that are

difficult to fully be described in complex ways and though a model maybe reproducing observed streamflow data well, we cannot be sure due to equifinality problems inherent in the modelling process which can be achieved partly by using a qualitative conceptual model.

- A further problem is the relevance of the original data sources with respect to the model structure and the physical meaning of the parameter values as much of the hydrogeological data available are always derived from other parameters. The extent to which this data is relevant at a sub-basin scale model is largely unknown and uncertain at present and therefore, further evaluations of hydrogeological data are necessary.
- The Modified Pitman and SWAT models' setups and operations in the watershed are both described in great length in the current study. It may serve as a good reference for future studies that may concentrate on hydrological modelling in locations with characteristics different from those in TMG areas.

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