

**HYDROLOGICAL MODELLING FOR ESTIMATING WATER AVAILABILITY FOR
IRRIGATION SUPPLY IN SELECTED SCHEMES IN NZHELELE AREA**

BY

MBAIMBAI V.

STUDENT NO.: 11640438

SUPERVISOR: PROF R. MAKUNGO

CO-SUPERVISOR: PROF J.G. NDIRITU

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DECLARATION

I, Mbaimbai Vhahangwele, hereby declare that this thesis for Master of Earth Sciences in Hydrology and Water Resources degree at the University of Venda is my work in design and execution. The thesis has not been submitted previously by anyone, for a degree at this university or any other university. All effort has been taken to acknowledge the material which was referenced.



Signature

12 August 2025

Date

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ABSTRACT

South Africa is one of the driest countries in the world, and its smallholder irrigation schemes - particularly in semi-arid regions like Nzhelele in Limpopo Province - are under growing pressure due to water scarcity and climate variability. Many of these schemes suffer from poor monitoring of water inflows and a lack of reliable data on crop irrigation needs. This study aimed to quantify irrigation water availability and determine whether current water resources can meet the crop water demands of three smallholder schemes - Mandiwana, Raliphaswa, and Mamuhohi. Objectives included simulating streamflow using hydrological modelling, estimating crop water requirements, and identifying which crops are sustainable under existing water supply conditions. The Soil and Water Assessment Tool (SWAT) was used to simulate streamflow from 1987 to 2014 using daily hydrometeorological data. Calibration and validation were performed over two distinct periods: 1991–2000 and 2001–2009. Reference evapotranspiration (ET_o) was calculated using the Hargreaves equation due to limited data, and crop coefficients (K_c) were used to estimate daily water needs for maize, sweet potato, groundnuts, and green beans. A 60% conveyance efficiency was applied to assess actual deliverable water. The model showed that maize and sweet potato had manageable water demands 540 mm and 475 mm in the dry season, respectively, while groundnuts and green beans had higher peak requirements that exceeded available supply. The SWAT model performed well, the R², NSE and PBIAS values for calibration and validation ranged from 0.78, 0.56, and 7.7%, and 0.60, 0.56, and -8.3%, respectively. These findings can guide crop selection and water allocation, offering practical insights for improving smallholder irrigation planning in water-limited environments.

Keywords: hydrological modelling, crop water requirements, SWAT, smallholder irrigation, water availability, Nzhelele

DEDICATIONS

This work is dedicated to my late brothers, Mbaimbai Tshamano and Mbaimbai Muvhuso Justice.

LIST OF ABBREVIATIONS/ACRONYMS

ANOVA	Analysis of Variance
CWD	Crop Water Deficit
CWP	Crop Water Productivity
CWR	Crop Water Requirement
DALRRD	Department of Agriculture, Land Reform and Rural Development
DF	Depleted Fraction
DHI	Danish Hydraulic Institute
DWS	Department of Water and Sanitation
E	Evaporation
CE	Conveyance Efficiency
ET	Evapotranspiration
ET ₀	Reference Crop Evaporation
ET _p	Potential Evapotranspiration
Epan	Evaporation pan
FAO	Food and Agricultural Organization
GIS	Geographic Information System
HRU	Hydrologic Response Units
K _c	Crop Coefficient
LNRBRD	Lower Niger River Basin and Rural Development
LULC	Land-use Land Classification
METRIC	Mapping Evapotranspiration at High Resolution and with Internalized Calibration
MRBC	Mahi Right Bank Canal
MSE	Mean Square Error
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash Sutcliffe Efficiency Coefficient
PBIAS	Percent Bias
r	Correlation Coefficient
RCSD	Resources Centre for Sustainable Development
RET	Relative Evapotranspiration
RMSE	Root Mean Square Error
RS	Remote Sensing

RWS	Relative Water Supply
SACS	South African Committee for Stratigraphy
SAPWAT	South African Program Water
SAVI	Soil Adjusted Vegetation Index
SAWS	South African Weather Services
SEBAL	Surface Energy Balance Algorithm for Land
SIS	Smallholder Irrigation Schemes
SANLC	South African National Land-Cover
SWAP	Soil Water Atmosphere Plant
SWAT	Soil and Water Assessment Tool
SWIM	Soil and Water Integrated Model
T	Transpiration
WGHM	Watergap Global Hydrology Model
WRC	Water Research Commission
WR2012	Water Resources of South Africa, 2012
WUAs	Water User Associations

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CHAPTER ONE: INTRODUCTION

1.1. Background

Classified as the 30th driest country in the world, South Africa receives about half of the average global annual rainfall (Schreiner *et al.*, 2010). According to De Villiers *et al.* (2004), over 60% of the country receives less than 500 mm of rainfall per annum, which is assumed to be the minimum rainfall required for successful dryland cropping, while about 21% receives less than 200 mm. Irrigated agriculture accounts for almost 30% of total crop production and is the largest user of water in the country, only 7% of the total area of the country receives an annual rainfall of more than 800 mm (Schulze, 1997).

Over the past 25 years, the consumption of water through irrigation has decreased from 80 to about 66% (National Water and Sanitation Master Plan, 2018) in South Africa but still, there is a need to improve the efficient use of water in irrigation farming (De Villiers *et al.*, 2004). This decline reflects a mix of improvements in efficiency through technology, conservation practices, and demand-management initiatives by DWS as well as the deteriorating condition of many irrigation schemes, which suffer from poor infrastructure, inadequate maintenance, and lack of monitoring (DWS, 2023).

In southern Africa, most governments embarked on large- and small-scale irrigation schemes mainly in areas that receive little total annual rainfall to supplement water shortages. This is another way of improving agricultural production. However, Chenje *et al.* (1998) suggested that in terms of empowering the local communal people, small-scale schemes are suitable as they occupy land which is readily available for agricultural activities to take place.

Van Averbek (2012) defined a smallholder irrigation scheme as an agricultural project that is constructed specifically for occupation by African farmers and involves multiple holdings, which depend on a shared distribution system for access to irrigation water and in some cases also on a shared water storage or diversion facility. Approximately, about 30% of the provincial land surface of the Limpopo Province is covered by smallholder farms that are mostly located in the former homeland areas (Odhiambo and Magandini, 2008).

Backeberg *et al.* (1996) reported that about 37% of farmers on smallholder irrigation schemes are involved in agriculture for commercial gain or to sell their products, while the other remaining 63% are mainly engaged in subsistence production, to feed their families (Makumbe, 1996). Therefore, it is of great importance that government, private agencies, and

the farming communities should be empowered towards achieving a sustainable smallholder irrigation scheme through adaptation of climate smart agriculture that will enhance food security in the province and in the country (Oni et al., 2011).

1.2. Statement of the problem

Smallholder irrigation schemes in the Nzhelele area of Limpopo Province play a critical role in sustaining rural livelihoods and food security. However, many of these schemes perform below capacity due to deteriorating infrastructure, weak management, and limited technical support (Mudau, 2010; van Koppen et al., 2017). Field assessments of Raliphaswa, Mamuhohi, and Mandiwana schemes revealed that inflows are not monitored, and crop water requirements are undocumented, leading to inefficient and unregulated irrigation practices.

Nzhelele is a semi-arid region with low and variable rainfall, high evapotranspiration rates, and competing water demands, all of which put pressure on fragile irrigation systems (van Averbeke, 2011; DWA, 2013). In the absence of reliable hydrological data and formal scheduling mechanisms, farmers rely on traditional knowledge rather than evidence-based planning, resulting in both water wastage and reduced productivity (Frenken, 2005; Speelman et al., 2008; Machete et al., 2004).

While hydrological models such as SWAT are widely used to support water resource planning, their application in smallholder schemes like those in Nzhelele is limited (Neitsch et al., 2011; Xie et al., 2014). Addressing this data and planning gap is critical to transforming these schemes into efficient, productive systems suited to South Africa's water-stressed context (Backeberg, 2003; Rosegrant et al., 2009).

1.3. Motivation

Smallholder irrigation plays a crucial role in enhancing food production, sustaining rural livelihoods, and supporting economic development in South Africa. However, one of the most notable observations is that smallholder farmers tend to apply significantly less water than is recommended for conventional full irrigation practices (DWA, 2007; Frenken, 2005). This under-irrigation may stem from a combination of water shortages, a lack of knowledge regarding crop water requirements, and inadequate system management. As a result, there is a pressing need to investigate actual water use in these systems and develop strategies to better align water availability with crop demand.

Given South Africa's semi-arid climate and increasing pressure on water resources, improving irrigation efficiency is critical for the sustainability of smallholder schemes. Estimating the actual irrigation water requirements can support practical interventions such as adjusted planting densities, improved irrigation scheduling, and the adoption of low-input cultivation methods (Balarane, 2015). This is particularly important in areas like the Nzhelele region, where rainfall variability and high evaporative demand further limit water availability for crop production.

Irrigation presents a valuable opportunity to overcome climate-related production limitations by stabilising yields and increasing land productivity. Yet in South Africa, irrigated land is often underutilised due to poor planning and weak integration of water availability data into decision-making processes (Yokwe, 2004; van Averbek, 2008). By understanding the spatial and temporal availability of water, farmers and planners can improve crop selection, irrigation scheduling, and economic returns. Moreover, successful smallholder irrigation schemes have the potential to become self-sustaining by generating revenue that supports the operation and maintenance of infrastructure (Backeberg, 2003; Rosegrant et al., 2009).

This study is therefore motivated by the need to generate site-specific data to improve the efficiency, productivity, and sustainability of smallholder irrigation schemes in water-stressed environments. By applying hydrological modelling and estimating crop water requirements in selected schemes in the Nzhelele area, the study aims to support evidence-based planning and inform future investments in smallholder irrigation development.

1.4. Objectives

1.4.1. Main objectives

To undertake hydrological modelling for estimating the availability of water for irrigation supply in selected smallholder irrigation schemes in Nzhelele area.

1.4.2. Specific objectives

- To calibrate and validate a hydrological model for estimating inflows into selected irrigation schemes in Nzhelele area.
- To estimate irrigation water requirements (crop water requirements) for the selected schemes.
- To compare the inflows and the irrigation water requirements.
- To recommend the types of crops that can be planted in the schemes

1.5. Research questions

- What is the quantity and reliability of water inflow into the selected smallholder irrigation schemes in the Nzhelele area, as estimated by hydrological modelling?
- What are the crop water requirements for key crops grown in the selected irrigation schemes?
- Can the available water meet the crop irrigation requirements under current conditions?
- Which crops are most suitable for cultivation under the available water supply in the selected schemes?

1.6. Study area

1.6.1. Location

The study area falls under quaternary catchments A80A and A80B of the Nzhelele River Catchment, located in the northernmost part of the Limpopo Province of South Africa. It is on the leeward side of the Soutpansberg Mountains. It lies between the longitude 22°54'00"S and latitude 30°12'00"E and covers a surface area of approximately 2,436 km². The three smallholder irrigation schemes selected for the study were Mandiwana, Raliphaswa and Mamuhohi. Mamuhohi is the largest of the three schemes with a land area of 92ha, followed by Mandiwana irrigation scheme with a land area of 66ha and lastly, Raliphaswa irrigation

scheme is the smallest of the three schemes, with a land area of 15ha. Figure 1. 1 shows the main features of the study area.

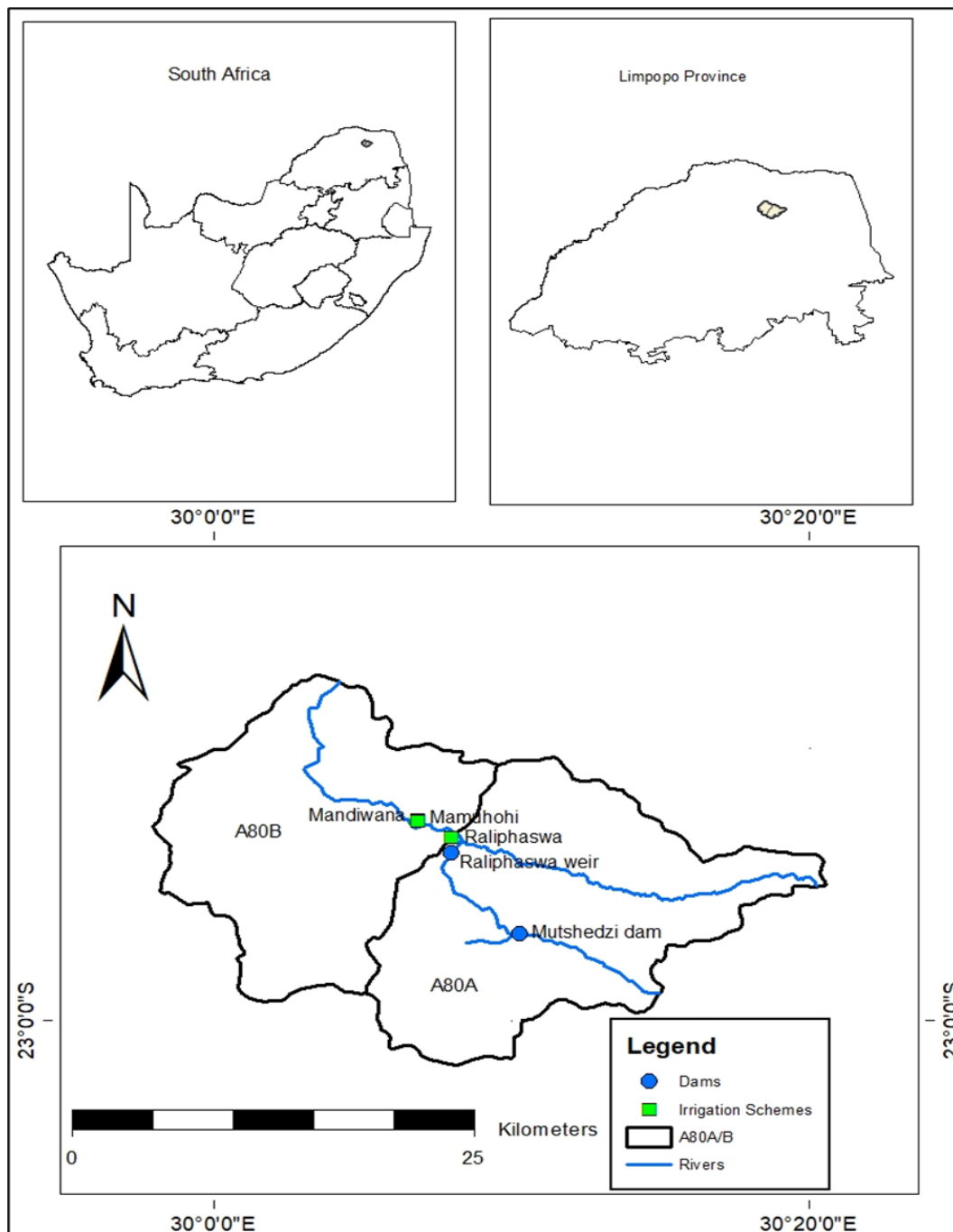


Figure 1. 1: Study area

1.6.2. Climate

Vhembe climate is typically subtropical, with mild, moist winters and wet, warm summers characterized by Lowveld (Arid and Semi-arid) (Poto and Mashela, 2008). The region is classified as a summer rainfall area, often characterised by thunderstorms with quick runoffs and there are months that experience no rainfall, a good month might expect to see rainfall

exceeding 170 mm (Mudau, 2010). The annual rainfall of approximately 500 mm per annum out of which about 95% falls between October and March (M'marete, 2003) occurs in the area. The rainfall pattern is largely influenced by the Orographic rain effect of the Drakensberg Mountains joining the Soutpansberg perpendicularly hence decreasing from east to west of the district. The annual temperature ranges from a minimum of 10°C during winter to a maximum of up to 40°C in summer.

1.6.3. Hydrology

The area is drained by the Nzhelele River which is one of the major tributaries of the Limpopo River System on the northern part of the area and covers an area of approximately 3436 km². The Limpopo River System is considered the life blood of the Northern Vhembe semi-arid area. Limpopo River is the country's third most important river which provides sustenance to the predominantly hot and drylands through which it meanders. A perennial river known as Mutshedzi, which is a tributary of the Nzhelele River flows through the study area and it is the one feeding the Raliphaswa weir.

1.6.4. Land use and soil types

The land is predominantly used for commercial/subsistence agriculture and rural settlements. Most of the land is used for settlement grazing and small-scale farming. Small-scale farming consists of a mixture of crops such as maize, mango, banana, avocado trees, and sugarcane. The types of crop soils in the Vhembe region are variable – tending to be sandy in the west, but with a higher loam and clay content towards the east. The soils are mainly developed on basalt, sandstone, and biotite gneiss and are generally of low inherent soil fertility and fragile (White Paper on Agriculture, 1995; Odhiambo and Magandini, 2008). Figure 1. 2 shows the land use found in the study area.

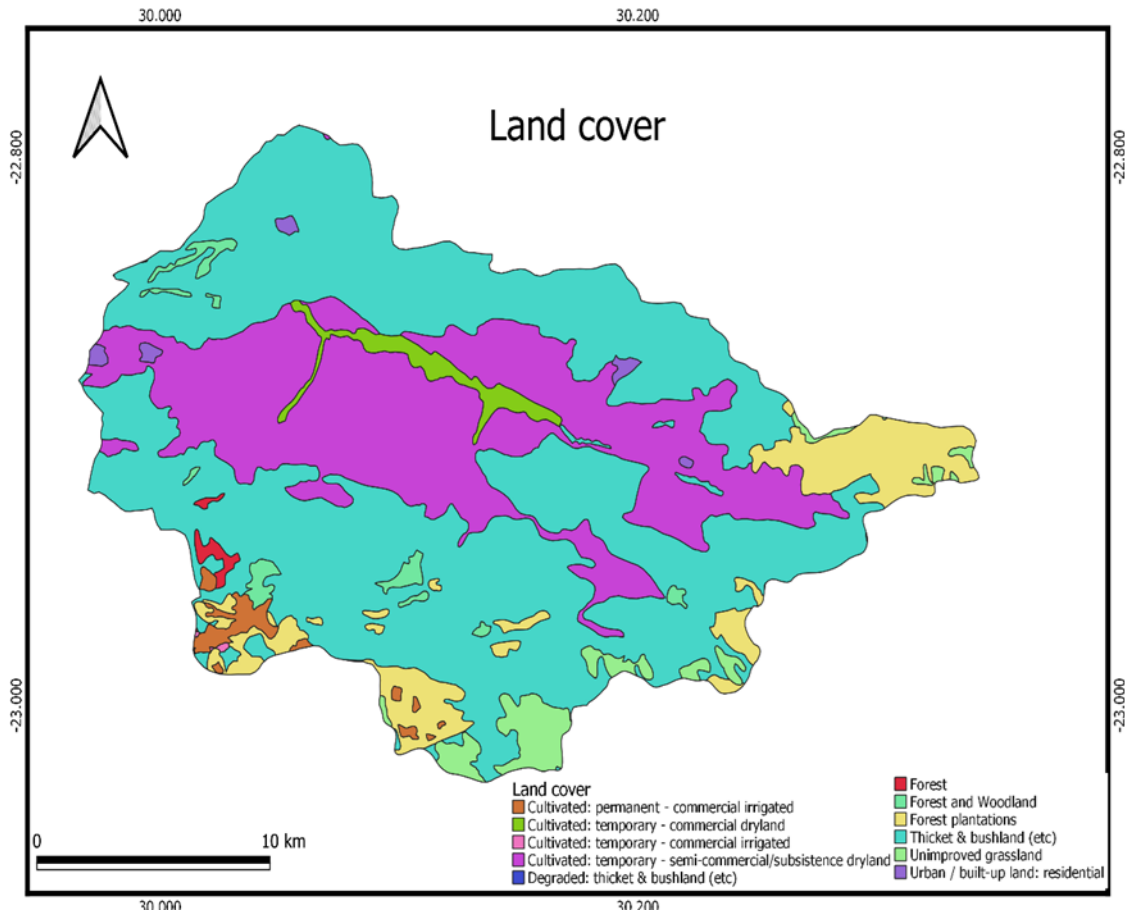


Figure 1. 2: Landcover/land-use map of the study area.

1.6.5. Geology

Figure 1. 3 shows the geology of the study area. The study area is underlain by basaltic rocks which are fine-grained volcanic rocks that fall within the Soutpansberg group and the Bandelierkop complex. The Soutpansberg group represents a volcano-sedimentary succession that is divided into six formations (SACS, 1980; Brandl, 1991) the Soutpansberg group can be divided into two formations, namely the Sibasa formation and the Wylliespoort. This group comprises a volcanic and sedimentary rock succession that is presently divided into six formations. The six formations are Tshifhefhe, Sibasa, Fundudzi, Wylliespoort, Musekwa, and Nzhelele (Brandl, 1991).

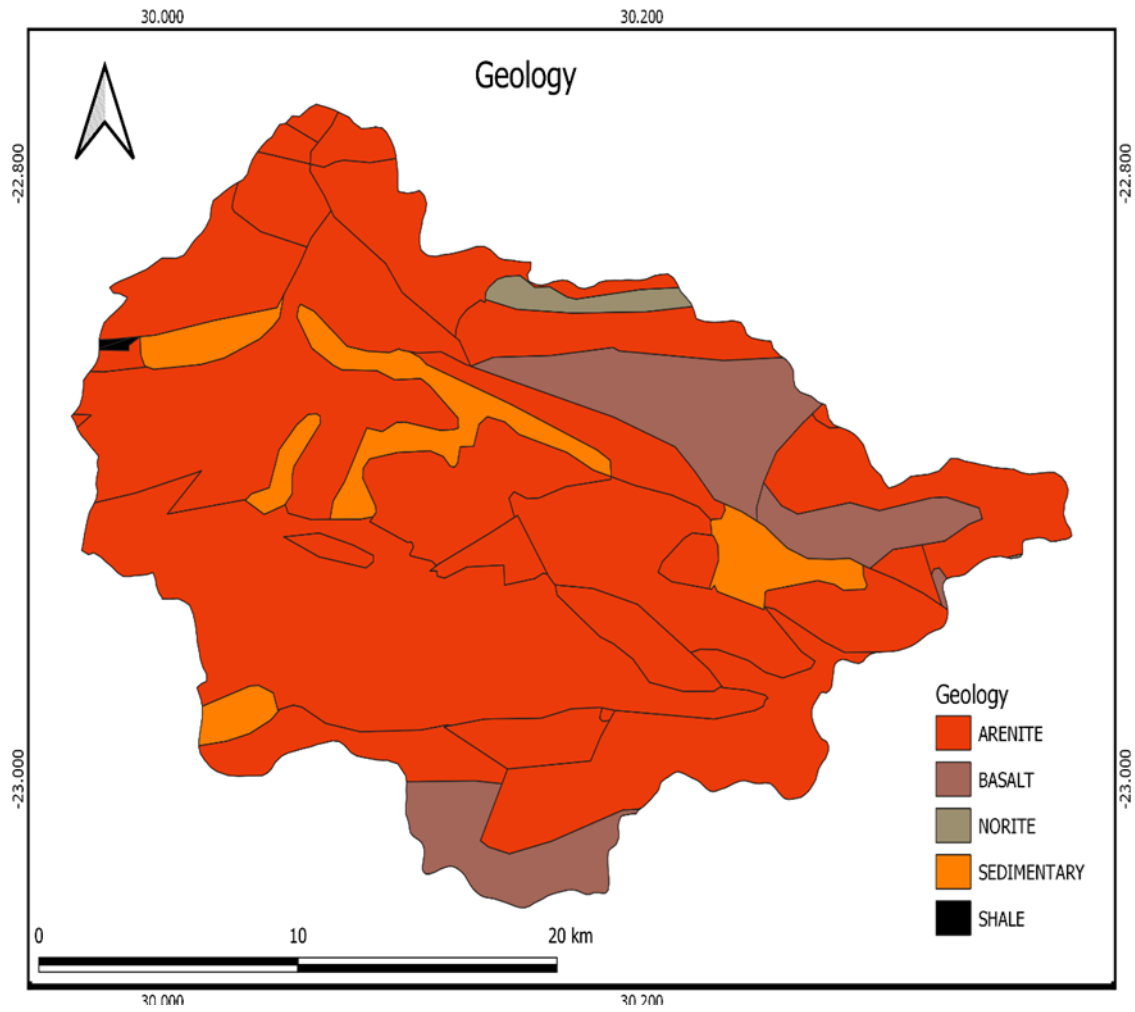


Figure 1. 3: Geology of the study area.

CHAPTER TWO: LITERATURE REVIEW

2.1. Preamble

This chapter reviews previous studies on smallholder irrigation schemes. It also reviews the methods used in modelling water availability for irrigation, crop water requirements and measures used to assess model performance.

2.2. Previous studies on smallholder irrigation schemes (SIS) and hydrological modelling

Smallholder irrigation schemes are critical to enhancing food security, improving rural livelihoods, and increasing resilience to climate variability (Namara et al., 2011; FAO, 2020). However, the success of these schemes often hinges on accurate estimation of water availability, which is influenced by seasonal rainfall patterns, catchment hydrology, and competing water uses (Mdemu et al., 2020). In semi-arid regions such as Limpopo Province, where the Nzhelele River basin is located, sustainable water management is essential due to high inter-annual variability in rainfall and limited water resources (Awulachew et al., 2022).

While SIS are critical in enhancing food security, hydrological modelling plays a pivotal role in understanding and managing water resources, particularly in regions facing climate variability, land use changes, and water scarcity. Among the widely used physically-based models, the Soil and Water Assessment Tool (SWAT) has emerged as a robust tool for simulating water balance, streamflow, and irrigation demand across varying climatic, geographic, and management conditions (Arnold et al., 2012; Gassman et al., 2014; Kishore et al., 2025).

Several authors have documented the benefits of smallholder irrigation schemes in enhancing crop yields, stabilizing food supply, and improving household income (Namara et al., 2011; Inocencio et al., 2007). According to Fanadzo (2012), smallholder irrigation schemes significantly contribute to food security and poverty reduction by providing a more reliable water supply than rain-fed agriculture.

Furthermore, Fanadzo et al. (2010) noted that irrigation enables crop diversification and the extension of cropping seasons, which allows farmers to generate income throughout the year. These schemes also play a role in women empowerment and improved household nutrition (Chazovachii, 2012).

Despite their potential, many smallholder irrigation schemes face numerous challenges, including poor maintenance, inadequate water governance, weak institutional support, and limited access to markets and finance (Van Auerbeke et al., 2011; Mutiro and Lautze, 2015). Poor operation and management systems often result in underperformance and infrastructure degradation (Denison and Manona, 2007).

Climate variability and change also threaten the sustainability of these schemes. Studies by Rockström et al. (2010) and Hagos et al. (2009) indicated that changing rainfall patterns can reduce water availability, leading to competition and conflict among users in already water-scarce regions.

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Previous research has evaluated the efficiency of water use in smallholder irrigation schemes, with findings pointing to low water productivity due to over-irrigation, conveyance losses, and poor scheduling practices (Pereira et al., 2002; Makombe et al., 2007). Improving irrigation efficiency requires better system design, capacity building for farmers, and introduction of modern irrigation techniques like drip or sprinkler systems where feasible (Molden et al., 2010).

Studies using models such as CROPWAT, SWAT, and AquaCrop have been employed to assess irrigation performance and optimize water use. For instance, Tesfaye et al. (2008) used simulation models to evaluate the performance of smallholder schemes in Ethiopia and found that improved scheduling significantly enhances productivity.

Also, in South Africa, the revitalization of smallholder irrigation schemes through government initiatives such as the *Revitalisation of Smallholder Irrigation Schemes (RESIS)* programme

has been studied by Denison and Manona (2007), who highlighted the need for technical, financial, and organizational support to sustain these initiatives.

Recent studies have effectively employed SWAT for simulating water balance components, particularly in data-scarce regions. For instance, Kishore et al. (2025) applied SWAT in the Mahanadi River Catchment, India, to evaluate surface runoff, evapotranspiration, and groundwater recharge under changing climate conditions. The study demonstrated high model performance ($NSE > 0.8$), with the SUFI-2 algorithm used for calibration. Similarly, Mengistu (2019) applied SWAT in an arid South African catchment and successfully simulated HRU-level water balance with satisfactory NSE and PBIAS values, despite limited data availability.

Yalcin (2019) used SWAT to estimate monthly irrigation return flows in the Kozluk Basin, Turkey, offering insights into groundwater recharge and basin sustainability. This kind of estimation is critical for determining effective water use and improving irrigation system efficiency, particularly in semi-arid zones.

In the context of irrigation planning, Gurley et al. (2023) used SWAT to project future streamflow and irrigation water demands in the Cape Fear and Pee Dee river basins under climate, land-use, and population scenarios. Their results highlighted seasonal water deficits and provided essential input for agricultural water management.

Teshome et al. (2020) conducted daily and monthly streamflow simulations in the Bina River Basin, India. The model yielded high correlation coefficients ($R^2 = 0.96$ at monthly scale), confirming SWAT's reliability in flow forecasting essential for water resource allocation and reservoir operations.

The development of SWAT+, an upgraded version of SWAT, has enabled more sophisticated water management simulations. Sánchez-Gómez et al. (2025) implemented SWAT+ in the Upper Tagus Basin, Spain, to evaluate water allocation for irrigation and reservoir operations. The study found that SWAT+ decision tables successfully simulated irrigation satisfaction and improved streamflow estimation, reducing PBIAS by over 50%.

2.3. Hydrological modelling of availability of irrigation water and crop water requirements estimation

According to Sorooshian *et al.* (2008), a model is a simplified representation of a real-world system, and the best model is the one that gives results close to reality with the use of

minimum parameters and model complexity. Models are mainly used for predicting system behavior and understanding various hydrological processes. A model consists of various parameters that define the characteristics of the model (Goyathri *et al.*, 2005). Hydrological modelling can be defined as the characterisation of hydrologic features and systems by use of small-scale physical models, mathematical analogs, and computer simulations (Allaby and Allaby, 1999). The hydrological models help in estimating water withdrawals and the quantity of water that is consumed and help regulators in quantifying hydrologic processes which are difficult to measure (Kuyawama *et al.*, 2017).

These models are a valuable tool for planning the sustainable use of water resources to meet various water demands. According to Arnold *et al.* (2012), the current modelling philosophy requires that models are transparently described and that calibration, validation, sensitivity, and uncertainty analysis are routinely performed as part of modelling work. Uncertainty analysis to evaluate the strength of a calibrated model is important since calibration is conditional, meaning that it is conditioned on the model structure, model inputs, analyst's assumptions, calibration algorithm, calibration data, and many other factors and is not uniquely determined.

A study on "Techniques for calibration and validation of SWAT model in data scarce arid and semi-arid catchments in South Africa" was conducted by Mengistu *et al.* (2019). The study was aimed at configuring, calibrating, and validating the SWAT model in a data-scarce catchment by using regionalization with a physical similarity approach. The approach used dual calibration and validation procedures, *i.e.*, one in the donor catchment (by using SWAT-CUP (SWAT Calibration and Uncertainty Programs) and the other in the study catchment (by manual calibration and verification). Based on the sensitivity analysis, SWAT-CUP calibrated sixteen parameters. The result from the uncertainty analysis indicated acceptable values of both the R-factor (0.8) and P-factor (0.7). The model performance evaluation also showed acceptable ranges of values (*e.g.*, NS was 0.76 and R^2 was 0.78). The main calibration and validation process was conducted outside the target catchment, though it was assumed that the donor and target catchments have similar hydrological responses. Therefore, the study suggested further inspection methods to minimise the model uncertainty in the study catchment.

2.4. Estimating inflows into irrigation schemes

The inflows water balance equation is used to estimate the inflows into irrigation schemes. Inflows can be defined as the source of water in a water body (for example, surface inflows or groundwater inflows) (Taghvaeian and Neale, 2011). Agricultural water balance analyses have been conducted at a wide variety of temporal and spatial scales in the past few decades. Information on the amount of water supplied to irrigation schemes and its occurrence is provided by the scheme-wide balance analyses. The main components of the water balance equation (Equation 2.1) of a field or irrigation system are given as follows (Jenson, 2007):

$$W_g = E + T + \Delta S + R_s + D \quad 2.1$$

where W_g is the gross volume of water delivered to a field or study area including effective precipitation, E is evaporation from the soil and plant surfaces, T is transpiration, ΔS is change in water stored in the root zone of the soil, R_s is surface runoff, and D is vertical drainage below the crop root zone that may be natural or enhanced with a subsurface drainage system. From Eq. 2.1, the first two terms represent liquid water that has been converted to vapor and transferred to the atmosphere. For many studies, it is not practical to separate E and T . Therefore, the combined E and T components are usually represented by the term evapotranspiration (ET). Surface runoff and vertical drainage often provide the water supply for downstream fields or projects within a hydrologic unit or river basin, or it returns to the underlying groundwater from which it was pumped. Water that is incorporated within plant tissue or the harvested component of a crop is usually an exceedingly small part of the water balance and is generally ignored in water balance and water management calculations.

2.5. Estimation of crop water requirements

FAO (2000) and Woyessa et al. (2004) defined crop water requirement as the amount of water required to compensate for the evapotranspiration loss from the cropped field. It represents the difference between the crop water requirement and effective precipitation and includes additional water for leaching salts and to compensate for the non-uniformity of water application. Woyessa et al. (2004) reviewed SAPWAT and CROPWAT methods which are used to estimate crop water requirement. These methods have become the international standard used on a global scale for irrigation management.

CROPWAT model

According to Smith (1992), CROPWAT is an irrigation management and planning model used in simulating the complex relationships of on-farm parameters the climate, crop, and soil. The CROPWAT model facilitates the estimation of crop evapotranspiration, irrigation schedule, and agricultural water requirements with different cropping patterns for irrigation planning and was developed by the Land and Water Development Division of the Food Agricultural Organization (FAO) (Smith, 1992). Since CROPWAT calculates the evapotranspiration and crop water requirements, it allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and yield reduction under various conditions (Muhammad, 2009).

The CROPWAT method allows the development of improved irrigation practices, planning of irrigation schedules, and assessment of production under rainfed conditions or deficit irrigation. It was also developed as a planning and management aid that is supported by extensive South African climate and crop databases. The CROPWAT model for Windows uses the FAO Penman-Monteith method to estimate the reference crop evapotranspiration (Allen *et al.*, 1998). According to Jensen *et al.* (1990), the Penman-Monteith method is more dependable than methods that use less climatic data. The Penman-Monteith equation for estimating the reference evapotranspiration is given in equation 2.2:

$$ET_0 = \left[\frac{0.48\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \right] \quad 2.2.$$

Where, ET_0 is the reference evapotranspiration in mm/a, R_n is the net radiation in MJ/(m²·d), G is the soil heat flux density in MJ/(m²·d), U_2 is the wind speed at a height of 2m (m/s), e_s is the saturated vapor pressure in kPa, e_a is the actual vapor pressure of the air at standard screen height in kPa, γ is the psychrometer constant in kPa/°C, Δ is the slope of the saturation vapor pressure curve between the average air temperature and dew point in kPa/°C, T is the mean daily air temperature in °C, ET_c is the crop water requirement (CWR) in mm/a and where K_c is the crop coefficient. ET_c can be calculated using the equation given in equation 2.3:

$$ET_c = K_c \cdot ET_0 \quad 2.3.$$

SAPWAT

SAPWAT is a computer program that was developed to satisfy a need for a user-friendly and credible aid to planning and management tool for the estimation of crop irrigation requirements by irrigation engineers, agriculturalists, managers, and farmers of irrigation schemes and for water management by Water User Associations (WUAs) (Crosby and Crosby, 1999). In the South African context, SAPWAT is a further development and improvement on the Green Book of 1985 which had been the basis of irrigation requirement planning for many years, but which has been overtaken by developments in irrigation practice and management, whereas on the international context, SAPWAT links to and is also a further development on an FAO planning model, CROPWAT, which, in turn, leans strongly on several FAO irrigation and drainage reports on irrigation management that have been published since 1977 (Crosby and Crosby, 1999; Van Heerden *et al.*, 2001; Van Heerden, 2004). When using long-term rainfall and evaporation time series altogether with a daily water balance model to compute irrigation requirements, SAPWAT assumes that potential crop evapotranspiration (ET_p) is directly proportional to the American class A-pan evaporation (E_{pan}), the ratio ET_p:E_{pan} being defined as the crop factor, also known as crop coefficient (Singels *et al.*, 2010).

Hargreaves Equation

The Hargreaves equation (Hargreaves, 1985) is an empirical temperature-based model for computing the ETo of different crops. The Hargreaves equations, which is the second-ranked temperature-based method that expresses reference crop evapotranspiration, is used as a representative expression for potential evapotranspiration (Hargreaves, 1981; Hargreaves *et al.*, 1985). The measured temperature is the only required data required by the Hargreaves ETo method. The main advantage of using the Hargreaves method is its simplicity and suitability in data-scarce environments, as it only requires maximum and minimum temperature data. While it is less physically based compared to the Penman-Monteith method, it provides a practical alternative where complete climatic datasets such as solar radiation, wind speed, and humidity are unavailable. The Penman-Monteith equation remains the FAO-recommended standard for estimating reference evapotranspiration, and its performance is highly dependent on the availability and quality of climatic input data (Allen *et al.*, 1998; Tabari *et al.*, 2013). Several studies that adopted the Hargreaves formula in estimating ETo showed that this equation may provide accurate ETo estimates for 10 days or longer time steps and this was seen in studies by Jensen *et al.* (1990), Hargreaves, (1994),

Henggeler *et al.* (1996), Droogers and Allen, 2002) and many more studies. This equation is linked to solar radiation and is expressed as given in equation 2.4 below:

$$ET_o = 0.0023RaTD^{0.5}(Ta + 17.8) \quad 2.4$$

Where ET_o is the Hargreaves evapotranspiration in mm/day. Ra is Extraterrestrial radiation in MJ/m²/day, TD is Temperature difference ($T_{max} - T_{min}$) in °C, Ta is Mean air temperature in °C.

After computing the ET_o , the crop water requirements were then computed using the crop coefficient approach as given in equation 2.5 (Doorenbos and Pruitt, 1975):

$$ET_c = ET_o \times K_c \quad 2.5$$

Where ET_c is the crop water requirements in mm/day, ET_o is the evapotranspiration in mm/day and K_c is the crop coefficient.

2.6. Hydrological modelling tools

Soil and Water Assessment Tool (SWAT)

SWAT is a river basin scale model that was developed to determine the influence of land management strategies on water, sediment, and agricultural chemical yields in vast, complex watersheds with varying soils, land uses, and management conditions over prolonged periods of time. At different scales, it is a computationally efficient hydrologic and water quality simulator (Abbaspour *et al.*, 2009; Arnold *et al.*, 2012 and Kim *et al.*, 2008). The program has been utilized in a variety of worldwide projects. (Narasimhan *et al.*, 2005, Gosain *et al.*, 2006, Abbaspour *et al.*, 2007, Yang *et al.*, 2007, Schuol *et al.*, 2008).

SWAT is a continuous time model that operates on a daily time step at basin scale. The objective of this model is to predict the long-term impacts in large basins of management and timing of agricultural practices within a year (that is, crop rotation, planting and harvest dates, irrigation, fertilizer, and pesticide application rates and timing) (Gosain *et al.*, 2006; Arnold *et al.*, 2012). It can be used to simulate the basin-scale water and nutrient cycle in landscapes whose dominant land use is agriculture. It can also help in assessing the environmental efficiency of the best management practices and alternative management policies. SWAT uses a two-level dis-aggregation scheme: a preliminary sub-basin identification which is conducted based on topographic criteria, followed by further discretization using land use and soil type considerations. Areas with the same soil type and land use form a Hydrologic

Response Unit (HRU) (Mauser Bach, 2009), a basic computational unit assumed to be homogeneous in hydrologic response to land cover change. According to Neitsch *et al.* (2002), the water balance equation is used in the SWAT model, and it is given in equation 2.6:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad 2.6$$

Where:

SW_t = Humidity of the soil, SW_0 = Base humidity, R_{day} = Volume of rainfall in mm, Q_{surf} = Surface run-off, W_{seep} = Seepage of water from the soil to underlying layers, E_a = Evapotranspiration, Q_{gw} = Groundwater runoff and t = Time in days. According to Arnold *et al.* (2012), when calibrating a physically based model like SWAT, it is important to remember that all model input parameters are kept within a realistic uncertainty range and that no automatic procedure can substitute for actual physical knowledge of the watershed. However, physical knowledge is limited due to a lack of adequate data. The SWAT model has been used in a lot of studies, including a study by (Gosain *et al.*, 2006, Schuol *et al.*, 2008, Faramarzi *et al.*, 2009 and Faramarzi *et al.*, 2013).

WaterGAP Global Hydrology Model (WGHM)

The WaterGAP Global Hydrology Model WGHM, which is a sub-model of the global water use and availability model WaterGAP2 is a model used to compute surface runoff, groundwater recharge and river discharge at a spatial resolution of 0.5°. For each of the 0.5° grid cells, WGHM computes a time series of monthly runoff and river discharge. By calculating daily water balances of soil and canopy as well as of lakes, wetlands and large reservoirs, runoff can be estimated (Döll *et al.*, 2003 and Schmied *et al.*, 2021). The WGHM consists of sub-models for each of the water use sectors irrigation, livestock, households, and industry (Döll and Lehner, 2002).

Irrigation water requirements are modeled as a function of cell-specific irrigated area, crop and climate, and livestock water use is calculated using livestock numbers multiplied by livestock-specific water use. The WGHM assumes that actual evaporation from open water bodies is equal to potential evapotranspiration, and runoff is the difference between precipitation and potential evapotranspiration (Döll and Schmied, 2012). WGHM (or any other hydrological model) cannot be expected to compute good runoff and discharge estimates by

only using independent data sets this is due to the complexity of the processes, the large scale, and the limited quality of the input data (Döll *et al.*, 2003).

MIKE SHE (Systeme Hydrologique European)

MIKE SHE is a deterministic, physically based, distributed model used for simulation of different processes of the land phase in the hydrologic cycle (Refsgaard and Knudsen, 1996). According to El-Nasr *et al.* (2005) and DHI (1999), the hydrological processes are modelled by finite difference representations of the partial differential equations for the conservation of mass, momentum, and energy, in addition to some empirical equations. The hydrological components, which include the movement of surface water, unsaturated subsurface water, evapotranspiration, overland channel flow, saturated groundwater, and exchanges between surface water and groundwater, can be simulated using the MIKE SHE model.

With respect to water quality, the MIKE SHE simulates sediment, nutrient, and pesticide transport in the model area and simulates water use and management operations, including irrigation systems, pumping wells, and various water control structures. Add-on modules developed by the Danish Hydraulic Institute (DHI) are used to evaluate different agricultural practices and environmental protection alternatives. According to DHI (2004), model components describing the distinct parts of the hydrologic cycle can be used individually or in combination depending on the choice of the study. To account for the spatial variations in catchment properties, MIKE SHE represents the basin horizontally by an orthogonal grid network and uses a vertical column at each horizontal grid square to describe the variation in the vertical direction. This is achieved by dividing the catchment into many discrete elements or grid squares and then solving the equations for the state variables for every grid into which the study area was divided.

Refsgaard (1997) stated that for a model to run, several parameters and variables must be given as input for each cell. Most data preparation and model set-up can be completed using GIS, ArcView, or MIKE SHE's built-in graphic pre-processor. The system has built-in graphics and a digital post-processor for model calibration and evaluation of both current conditions and management alternatives. According to Abu El-Nasr *et al.* (2005), this model makes predictions that are distributed in space, with state variables that represent local averages of storage, flow depths, or hydraulic potential. Because of the distributed nature of the model, the amount of input data required to run the model is rather large, and it is rare to find a watershed where all input data required to run the model has been measured.

Global water resources model H08

The global water resource model H08 is used to estimate global water scarcity and is divided into six sub-models, which include land surface hydrology, river routing, crop growth, reservoir operation, water withdrawal, and environmental flow requirement (Hanasaki *et al.*, 2012). The land surface hydrology sub-model is a single soil layer model which is used to solve both the surface energy and water balance. The river sub-model is a single reservoir model which assumes a constant flow velocity. The crop growth sub-model is a process-based crop phenological model based on the formulation of the SWIM (Soil and Water Integrated Model) (Krysanova, 2000).

This sub-model is used to estimate the crop calendar (for example, planting date, harvesting date, and cropping period), which is vital in the estimation of the daily irrigation water requirement. The reservoir operation sub-model determines the storage and release of 507 reservoirs worldwide with a storage capacity larger than $1.0 \times 10^9 \text{ m}^3$ (Hanasaki *et al.*, 2006). Every reservoir is individually located on the river map of H08. Reservoirs with irrigation water supply as the primary purpose, the release is controlled to match the seasonal variation of potential agricultural water consumption demand in the lower reach. For reservoirs with other purposes, release and storage are controlled to minimize seasonal and interannual variations in river flows, considering the ratio of the storage capacity of reservoirs and mean annual inflow.

The environmental flow requirement sub-model is a simple empirical model which is used to estimate the amount of river discharge that should be kept in the channel to maintain the aquatic ecosystem. According to Hanasaki *et al.* (2012), the model is based on case studies of regional practices, while the river discharge should ideally be unchanged for the preservation of the natural environment. The water withdrawal sub-model withdraws water from rivers to meet potential water consumption demand. Notice that only consumptive water use is included and not return flow and delivery loss. When large reservoirs are in the upper stream, the river is affected by reservoir operation. H08 prioritises the simulation of municipal water withdrawal followed by industrial and agricultural water withdrawal.

PITMAN model

Pitman (1973) created the Pitman model to simulate runoff from South African catchments that are both gauged and ungauged. The Pitman model, which is the catchment process module of the Water Resources Simulation Model 2000 (WRSIM 2000) (Pitman *et al.* (2000))

and the previous version (WRSM 90) (Midgley et al. (1994)), is widely used in South Africa. The WRSM model has been modified to accurately depict highly developed South African catchments and is widely used for assessing water resources in the country (Bailey, 2008).

The monthly rainfall and yearly pan evaporation data are the two primary input data sets used by the Pitman model. Additionally essential for directing the model calibration procedure are the observed flows. It should be noted that rainfall data is the single most crucial input for the Pitman model's runoff simulation. The widespread knowledge that rainfall data collection is generally more spatially representative than available flow measurements and that periods of observation are often longer for rainfall data than for streamflow data is one of the primary underlying factors behind the usage of rainfall-runoff models (Mwelwa, 2004).

The catchment area, a time series of catchment average rainfall, seasonal distributions of evaporation (fractions), irrigation water demand (mm), other water needs (fractions), and monthly parameter distribution factors are mandatory data requirements for the rainfall-runoff model. Time series of watershed average potential evaporation, upstream input, transfer inflow, and downstream compensatory flow needs are examples of optional data requirements (Mwelwa, 2004).

Pitman (1973) offers broad guidelines for calibrating the PITMAN model across various climate types. These guidelines offer insight into which aspect of the simulation outcomes will primarily be influenced by adjustments to different parameter values. Usually, the Pitman model is manually calibrated, and some of its twelve parameters are kept at fixed values. Pitman (1973) suggested commencing calibration with the initial parameter values, while Midgley *et al.* (1994) gave preliminary Pitman model parameter values for the whole of South Africa.

In any calibration process, it is crucial to define a set of principles that are consistently applied to all catchments (Mwelwa, 2004). This approach is essential because, similar to any model with numerous parameters, there is considerable interaction among parameters, and there may not always be a unique set of values that produces a distinct outcome. To account for particular conditions, different researchers have employed modified versions of the original model, including Hughes (2013); Hughes (1997); Ndiritu and Mkhize (2017); Gan *et al.* (1997); Hughes *et al.* (2023) and Hughes and Metzler (1998). Recently, Bailey (2008) improved the modeling of highly developed South African catchments using the WRSM 2000 model.

While manual calibration has been the primary approach for the Pitman model, there have been instances of reported automatic calibration. Gan *et al.* (1997) conducted a comparative analysis involving five models, including the Pitman model, across four catchments. Although the SCE-UA method was utilized for all calibrations, the primary focus was not on assessing the adequacy of calibration. Using a genetic algorithm (GA), Ndiritu (2001) calibrated the Pitman model for two catchments in South Africa. The objective function was found to have very close values in several randomly initialized calibrations, and the crucial parameters that produced very close values in the various runs were easily determined. The derived parameter sets were regarded as global optima in practice.

Calibrating the Pitman model presents a multi-objective challenge because it requires aligning three key performance objectives which are mean annual runoff, standard deviation, and seasonal index between historical and simulated flows. According to Vrugt *et al.* (2003), the use of multiple objectives acknowledges that a single objective function is frequently an insufficient measure of the significant properties of the observed data.

Agricultural Catchments Research Unit (ACRU) model

The ACRU model is a conceptual agro-hydrological model that is mostly used on a daily time step (Schulz, 1995 and Smithers *et al.* (1997, 2018)). The model can simulate streamflow volume, peak discharge and hydrograph, reservoir yield, sediment yield, crop yield for specific crops, irrigation supply and demand, and many other significant hydrological cycle events that have an impact on the soil water budget. Taking climate, land use, and soil variability into account, ACRU can function at a point as a distributed cell-type model or as a lumped catchment model.

In cases when rainfall data that are automatically recorded are unavailable, the model may create hydrographs that utilize synthetic rainfall distributions for disaggregating daily rainfall into shorter time intervals. With time increments of less than a day, the model incorporates the simulation of lagging, and attenuation effects on the hydrograph as it moves through a reservoir or river reach are also modelled (Smithers *et al.*, 1997).

According to Smithers *et al.* (1997), a modified SCS method is used in ACRU to simulate stormflow depth. Instead of a curve number, the soil moisture deficit is obtained from a daily water balance of the soil profile. The baseflow and stormflow are added together daily to determine the volume of streamflow. The ACRU model simulates peak discharge within individual sub-catchments by employing the SCS triangular-shaped unit hydrograph

technique. When automatically recorded rainfall data with time intervals shorter than a day are not available, daily rainfall totals can be divided into shorter time segments using synthetic design rainfall distributions, as described by Weddepohl (1988) for southern Africa. This facilitates the generation of incremental storm hydrographs for each time interval.

These hydrographs are subsequently combined to construct the stormflow hydrograph at the outlet of each sub-catchment. The modeling approach for design flood estimation involves routing hydrographs from the outlet of one sub-catchment through the subsequent downstream sub-catchment until reaching the outlet of the final downstream sub-catchment. These hydrographs are then incorporated into the hydrographs generated for both the downstream sub-catchment and all other upstream sub-catchments that directly contribute to the flow of the downstream catchment. This methodology is elaborated upon by Smithers and Caldecott (1993, 1995). The ACRU model has been utilized in different agro-hydrological studies in and out of South Africa, including studies by Kienzle (2011), Aduah *et al.* (2017), Otim *et al.* (2020) and Rowe (2019).

2.7. Model sensitivity analysis, calibration, and validation

To verify the accuracy of the model's results, hydrological tests such as sensitivity/uncertainty analysis, calibration, validation, and statistical measurements are required (Gassman *et al.*, 2014; Gyamfi *et al.*, 2016). As a result, before utilizing a model for hydrological analysis, it is necessary to do a sensitivity analysis, calibrate, and validate the model for the catchment characteristics in which it will be used (Refsgaard and Storm, 1996; Golmohammadi *et al.*, 2014). This is because each study area or catchment is unique, and some criteria may differ from catchment to catchment based on the environment, land use, and soil (Arnold *et al.*, 1998). A model is calibrated and confirmed by comparing simulation results to existing observed data and then altering parameters so that the simulation results fit the known data period (Viessman *et al.*, 1989; Mutenyo *et al.*, 2013).

2.7.1. Sensitivity analysis

A huge number of parameters influence catchment dynamics, resulting in a significant number of uncertainties in distributed hydrological models (Rostamian *et al.*, 2008). A sensitivity study is the initial step in the calibration and validation process. According to Arnold *et al.* (2012b), the process of assessing the effect of changes in model parameter values to the modelling performance is known as sensitivity analysis. The two types of sensitivity analysis are local (done one at a time) and global. Using the SWAT-CUP SPE tool, a global

sensitivity analysis was carried out for this investigation. According to Arnold *et al.* (2012b), a difficulty with local sensitivity analysis is that the sensitivity of one parameter frequently depends on the value of the other relevant parameters. Another issue is that performing a lot of simulations is necessary for a global study. However, this study used 500 simulations for calibration, which was a significant quantity to get accurate results for global sensitivity analysis.

2.7.2. Calibration

Models must be calibrated to minimise predicted errors because of the various processes that occur in a watershed and uncertainties of modelling parameters (Gyamfi *et al.*, 2016). As a result, calibration is utilised to fine-tune the settings until the simulated and recorded streamflow data match as closely as achievable (McCuen, 2003; El-Nasr *et al.*, 2005). The calibration technique determines suitable values for user-specified parameters by estimating values for parameters that cannot be directly measured from field data (Refsgaard and Storm, 1996; Fadil *et al.*, 2011). The calibration procedure can be done manually or automatically using an optimisation algorithm that aims to minimise the objective function to show the difference between a measured and simulated stream flow series (Abbaspour, 2015). The auto-calibration option is less time-consuming and can be utilised to mitigate the risks associated with manual calibration (Fadil *et al.*, 2011).

2.7.3. Validation

Validation is the process of testing a calibrated model against data other than that used for calibration to confirm that it is suitable for later usage (Refsgaard and Storm, 1996). According to Mutenyo *et al.* (2016), model validation is a procedure for demonstrating that the model can provide correct simulations based on the project objectives. As a result, a second period of record is used to conduct validation, control, and check the accuracy of the parameters produced from the first period of record's calibration (Manaswi and Thawait, 2014). Refsgaard and Storm (1996), mentioned that validation means that a site-specific model may yield simulation results that are accurate for a specific study region.

2.8. Data quality control

According to Sattari *et al.* (2017), completeness and quality of data complements data analysis. Several studies have emphasised the need for data quality control for any data intended for use in hydrological or water resource analysis (Nkuna and Odiyo, 2011). Data

quality is impacted by the method used to collect data from the field, with human factors being the main considered aspect. Properly collected data gives absolute measures of data quality (Branisavljevic *et al.*, 2009). During data measurements, different errors such as random and systematic errors may be introduced in the observation recording of the data. Therefore, data quality control is useful and necessary in determining reliability and minimizing such errors (Foken *et al.*, 2004). According to Kundzewickz and Robson (2000), the analyst must not assume that the data is of good quality and should always check for data quality problems to ensure that data is acceptable, consistent, accurate and reliable when utilized.

2.9. Measures of model performance

Different statistical methods have been used to measure performance of hydrological models. The model performance measures used to determine efficiency of model calibration and validation include the Nash Sutcliffe efficiency coefficient (NSE), the overall root mean square error (RMSE), correlation coefficient (R^2) and the percent bias (PBIAS). Comparisons of simulated and observed measurements for multi-response validation may be integrated into the evaluation procedure to assess overall modelling performance in distributed hydrological modelling approaches (Krause *et al.*, 2005). These techniques are also applied in the evaluation of the relationship between the observed and estimated data.

2.9.1. Nash Sutcliffe Efficiency Coefficient (NSE)

The Nash Sutcliffe coefficient of efficiency expresses the proportion of variance of the recorded runoff that can be accounted for by the model and provides a direct measure of ability of the model reproduce the recorded flows (Boughton, 2006) and to assess the predictive power of hydrological models. The NSE can range from $-\infty$ to 1. An efficiency of 1 ($E = 1$) indicates a perfect match of modelled flows to the observed data (Boughton, 2006, Dile *et al.*, 2014 and Arnold *et al.*, 2012a). Moriasi *et al.* (2007) stated that values which are ≤ 0.0 indicate that the mean observed value is a better predictor than the simulated value which indicates unacceptable performance. According to Chiew and McMahon (1993), E values greater than 0.6 indicates a reasonable modelling of runoff while E values greater than 0.8 indicates a good modelling of runoff. Nash and Sutcliffe, 1970 and Moriasi *et al.*, 2007, computed Nash Sutcliffe Efficiency Coefficient using the formula:

$$E = 1 - \left[\frac{\sum_{i=2}^n (A_i^{obs} - F_i^{pred})^2}{\sum_{i=1}^n (A_i^{obs} - A^{mean})^2} \right] \quad 2.7$$

Where A_i^{obs} is the observed value, A^{mean} is the mean of observed data for the constituent being evaluated, F_i^{pred} is the predicted values and n is total number of observations. According to McCuen *et al.* (2006), the Nash–Sutcliffe efficiency coefficient is a widely used and potentially reliable statistic for assessing the goodness of fit of hydrologic models; however, a method for estimating the statistical significance of sample values has not been documented. If properly interpreted, Nash–Sutcliffe index can be a reliable goodness-of-fit statistic. Legates and McCabe (1999) mentioned that E is the ratio of the mean square error, which is given by the formula:

$$MSE = \frac{1}{n} \sum_{i=1}^n (A_i - F_i)^2 \quad 2.8$$

Where n is the total number of observations, A_i is the observed value and F_i is the predicted value. According to Karunanithi *et al.* (1994) and Carpenter and Barthelémy (1994), MSE provide information about the performance of the model in high flow situations. MSE depends on the units of estimated and observed values and varies on the interval. MSE value which is equal to 0 means that there is a perfect fit. Values of MSE less than half the standard deviation of measured data may be considered as low and that is either appropriate for model evaluation (Singh *et al.*, 2004).

2.9.2. Correlation coefficient (r)

The r describes the degree of co-linearity between simulated and measured data. A perfect positive linear relationship and if $r = 1$, a perfect positive linear relationship is said to exist between simulated and measured data (Moriasi *et al.* 2007). According to Van Liew *et al.* (2007), r values greater than 0.5 are considered acceptable. The correlation coefficient, which ranges from -1 to 1 , is an index of the degree of linear relationship between observed and simulated data. If $r = 0$, no linear relationship exists. If $r = 1$ or -1 , a perfect positive or negative linear relationship exists (Yuan and Lin 2006; Santhi *et al.*, 2001; Van Liew *et al.*, 2003). The r is computed using the formula:

$$r = \frac{\frac{1}{n} \sum_{i=2}^n (t_i - \bar{t}_i) (O_i - \bar{O}_i)}{\sqrt{\frac{1}{n} \sum_{i=1}^n (t_i - \bar{t}_i)^2} \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - \bar{O}_i)^2}} \quad 2.9$$

Where n is the total number of data points, t is the target, $\bar{t}$ is the mean of t , O is the output, and $\bar{O}$ is the mean of O . According to Legates and McCabe (1999), the correlation coefficient

has been widely used for model evaluation even though it is oversensitive to high extreme values and insensitive to additive and proportional between models predicted and observed data.

2.9.3. Root Mean Square Error (RMSE)

According to Shamsudin and Hashim (2002), the RMSE values for perfect agreement between observed and simulated values tends to be zero. The RMSE varies with the variability within the distribution of error magnitudes and with the square root of the number of errors ($n^{1/2}$), as well as with the average-error magnitude (Willmott and Matsuura, 2005). According to Chu and Shirmohammadi, 2004; Singh *et al.*, 2004; Vasquez-Amábile and Engel, 2005, RMSE is one of the most used error index statistics. Singh *et al.*, (2004) have published a guideline to qualify what is considered a low RMSE based on the observations standard deviation though it is commonly accepted that the lower the RMSE the better the model performance. It is computed using the formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad 2.10$$

Where P_i is the simulated value, O_i is the observed value and n is the total number of observations in the considered period (El-Nasr *et al.*, 2005). Lower RMSE means better model simulation performance.

2.9.4. Coefficient of determination (R^2)

According to Enders (2022), in the context of linear regression, R^2 is a measure that assesses a model's ability to predict or explain an outcome. R^2 denotes the proportion of variance in the dependent variable (Y) predicted or explained by linear regression and the predictor variable (X) also known as the independent variable. The R^2 is regarded as a standard metric in hydrology for evaluating the 'goodness-of-fit' between model simulations and observations (Barber *et al.* 2019). A high R^2 value is associated with an effective model (Quinino *et al.* 2013). Intuitively, model performance with $R^2 = 0$ is poor while a model with R^2 with a value of 1 denotes a perfect fit and, as such, is said to be a highly reliable model for future forecasts. Importantly, there are clear statements in the literature about using R^2 to evaluate model performance. Coefficient of determination is determined using the formula:

$$R^2 = \left[\frac{\sum_{i=1}^n (O_i - \bar{O}) S_i - \bar{S}}{(\sum_{i=1}^n (O_i - \bar{O})^2)^{\frac{1}{2}} (\sum_{i=1}^n (S_i - \bar{S})^2)^{\frac{1}{2}}} \right]^2 \quad 2.11$$

Where O_i = observed variable, S_i = simulated variable, $\bar{O}$ = mean of observed variable, $\bar{S}$ = mean of simulated variable, n = number of observations under consideration.

2.9.5. Percent bias (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Moriassi *et al.*, 2007; Gupta *et al.*, 1999; Yapo *et al.*, 1996). The optimal value is 0% while the positive values indicate a tendency to overestimate whereas the negative values indicate a tendency to underestimate the simulated flows. According to Moriassi *et al.*, (2007) acceptable values of PBIAS should be within $\pm 25\%$.

$$PBIAS = \left[\frac{\sum_{i=1}^n (A^{obs} - A^{sim}) * (100)}{\sum_{i=1}^n (A^{obs})} \right] \quad 2.12$$

Where PBIAS is the deviation of data being evaluated and is expressed as percentage, A^{obs} is the observed value, A^{sim} is the simulated data and n is the total number of observations. Gupta *et al.*, (1999) stated that PBIAS can indicate poor model performance clearly and that

CHAPTER THREE: METHODOLOGY

3.1. Preamble

This chapter outlines the research methodology. It explains the data collection methods and instruments that were employed in this research. It also provides detailed information about the methods which were used to analyse data to meet the objectives of the study.

3.2. Data collection

3.2.1. Data required for hydrological modelling

➤ Hydrometeorological data

Monthly naturalised streamflow data for catchment A80B, gauging station A8H011 and A8H001 were downloaded from the WR2012 website and were used for flow analysis, calibration, and validation of the model. Rainfall data for three stations (Veermedling, Mphefu, and Joubertstroom) were obtained from the South African Weather Services (SAWS). Hydrological data required include rainfall, evapotranspiration, runoff, and humidity and this was used in estimating water availability in the study area.

Daily temperature, rainfall, wind speed, relative humidity, and solar radiation for station p229303, a virtual station within the study area, were downloaded from the SWAT website (<https://swat.tamu.edu/>). Meteorological data were used to understand the rainfall patterns and how it affects water availability for irrigation and for hydrological modelling in the study area.

Table 3.1 shows information about all the data that were used in the study whereas Figure 3.1 shows the location of the stations.

Table 3.1: Hydrometeorological stations used

Station code or name	Longitude	Latitude	Variables	Data period	Start year	End Year
p229303	30.31	-22.95	Rainfall, temperature, wind speed, relative humidity, and solar radiation	35 years	1979	2014
Veermedling	30.16	-23.02	Rainfall	27 years	1987	2014
Mphefu	30.12	-22.91	Rainfall	27 years	1987	2014
Joubertstroom	30.15	-22.98	Rainfall	27 years	1987	2014
A8H001	30.070	-22.793	Streamflow	14 years	1932	1946
A8H011	30.163	-22.943	Streamflow	8 years	1991	1999

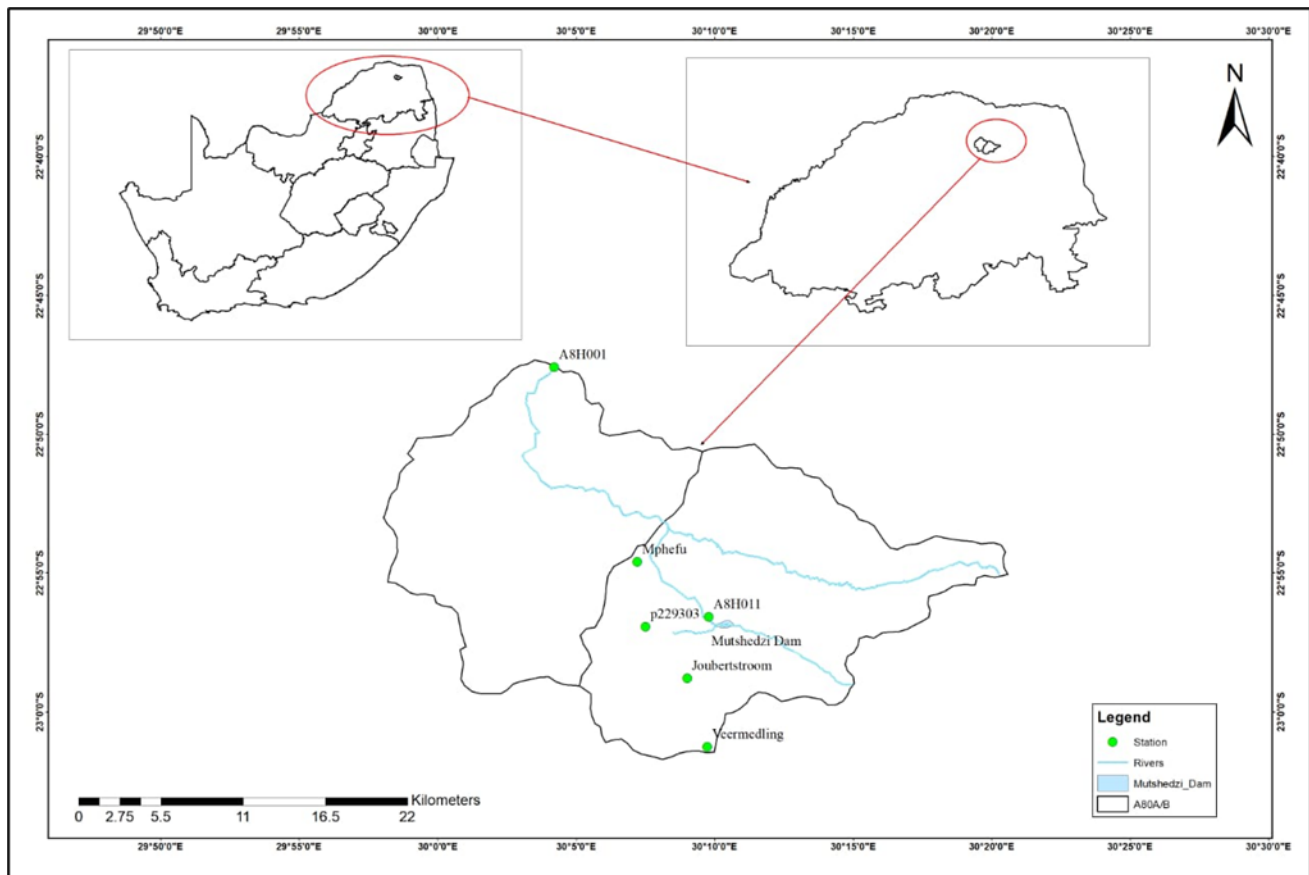


Figure 3. 1: Location of the hydrometeorological stations used.

➤ **DEM and land cover**

Digital elevation map (DEM) of 30m spatial resolution from Shuttle Radar Topography Mission (SRTM) was downloaded from the Regional Centre for Mapping of Resources for Development (RCMRD) Geoportal and it was used to delineate the watershed of catchment area. The digital elevation model is an important dataset because it derives all the topographic attributes of the catchment, sub-catchment, and HRUs level. Area, slope, slope length, channel length, channel slope, channel width, and channel depth are some of the DEM attributes. Land-use map for the year 2018 was obtained from the South African National Land-Cover (SANLC) and was used to generate projected land-use/landcover map that is required as input in SWAT model.

➤ **Slope**

The term slope is used to describe the nature of a place, such as whether it is mild or steep and referred to as the degree to which a soil surface is inclined relative to the horizontal. The SWAT model come with built in slope classes. To determine the study area's slope type, five classes (percentages) were chosen from a range of 0 - 10, 10 - 20, 20 - 30, 30 - 40, and 50

– 99%. The capacity of the model to preserve the topography's spatial diversity is influenced by the slope selection, which is based on various slopes.

➤ **Soil data**

Soil data including soil mapping units and soil properties were obtained from Agricultural Research Council Institute of Soil, Climate and Water (ARC-ISCW) and were used to map the different soil types underlying the study area. The USDA soil texture was used to determine the hydrological soil group of each type of soil that is found in the study area USDA (2009, 1987).

3.2.2. Data for estimating inflows into Raliphaswa weir

The data required for the estimation of inflows into the Raliphaswa weir are the same data that were used for building, calibrating, and validating the SWAT model. These include rainfall, temperature, windspeed, relative humidity, solar radiation and streamflow data downloaded from the SWAT website, SAWS and WR2012. The inflows for the period 1991 to 2009 were simulated after model calibration and validation. This was because the data that were used for model calibration and validation ended in the 2009.

3.2.3. Data for estimating crop water requirements and the extent to which available water could meet those requirements.

Field and questionnaire surveys were undertaken to allow understanding of the physical features of the catchment area and irrigation practices. Three irrigation schemes (Mamuhohi, Mandiwana and Raliphaswa) were visited to find out how water is conveyed from the river through a weir to the irrigation scheme. It was found that a night storage dam supplies water to the Mamuhohi scheme. Other irrigation data and data on crop factors were obtained from Allen *et al.* (1998). Farmers were interviewed to find out the farm size, area under irrigation, data on how they irrigate their farms (irrigation scheduling data) and information about the different types of crops planted. This information was useful in estimating crop water requirements.

The main questionnaire survey was conducted over the months of July to October 2021 and managed to interview 56 of the 114 farmers in the three schemes, i.e. 16 from Mandiwana, 7 from Raliphaswa and 33 from Mamuhohi. There were challenges in scheduling the interviews and in having the farmers available to undertake the long interviews. The survey data were compiled in spreadsheet format and are presented separately as Appendix A.

To determine the extent to which the available water can meet the crop water requirements, the computed daily crop water requirements of different crops in different cropping seasons and the areas under irrigation were used. This information was then used in recommending the types of crops that can be planted in the schemes.

3.3. Ethical Consideration

Prior to the commencement of this study, ethical clearance certificate was sought from the University of Venda Ethics Committee (Appendix C). The study complied with the code of ethics which has been proposed by the University of Venda. In addition, permission to conduct the research was sought from the Limpopo Department of Agriculture. Negotiations for entry into the study area was done with community traditional leaders (i.e., the Chief and the village Headman) and extension officers in each of the three selected irrigation Schemes. In line with the views of De Vos *et al.* (2011), the following key ethical principles underpinned the execution of the study.

The researcher enlightened the participants of the general nature of the research, which included the expected duration of their participation, the proceeding of the interviews and questionnaire, possible advantages and disadvantages and dangers of the participants that they may be exposed to, so they can make an informed decision on whether to participate in this study (Creswell and Cresswell, 2017). Also, a written consent form entailing brief information of the study was handed to each participant to sign and commit to participate in the study (Appendix B). Furthermore, in line with the informed consent principle, the participants were further informed to withdraw from participating in the study at any level of data collection. The participants were guaranteed that all the information obtained from them will not be made known to anyone other than the researcher, thus it was very confidential and their responses will be made anonymous. It was made known to the participants that there was no foreseen research related injury except any unforeseen issues they may face on their everyday lives. Moreover, participants were informed of the voluntary participation and that there are no research related costs which they will have to cover.

3.4. Data analysis

3.4.1. Hydrological modelling of water availability

To determine the availability of irrigation water in three irrigation schemes (Mahuhohi, Mandiwana and Raliphaswa), the SWAT model (Arnold *et al.*, 2012a) was used. The model

is designed to estimate surface runoff, evapotranspiration, baseflow, and agricultural and soil moisture change for each HRU. The SWAT model was selected because it was able to model the variables of interest in the study. The SWAT model has been used successfully to model catchments in South Africa and beyond (Eckhardt and Arnold, 2001; Arnold *et al.*, 2012a; Douglas-Mankin *et al.*, 2010).

Calibration and validation of the SWAT model were done using historical years data. Historical year's data were also used for the evaluation of the model performance. Parameters of the SWAT model were automatically calibrated based on sensitive parameters and a physical understanding of the catchment. Evaluation of model performance for both calibration and validation run was done based on selected performance measures, which include R^2 , Percent bias (PBIAS), and Nash Sutcliffe efficiency coefficient (NSE). Comparisons of available water and irrigation water requirements were done to determine the extent to which the water requirements can be met. This also aids in establishing cropping areas and types of crops that can be planted. These were useful in verifying the reliability of the model results.

➤ **Model set-up**

Model set-up for this study was done using the procedures applied by Sohel (2012), Jayakrishnan *et al.* (2005) and Duraes *et al.* (2011). The set-up was integrated using ArcSWAT, which is an ArcGIS extension, and an interface of SWAT, whereas DEM, soils, and land-use data sets were used in a GIS format. Following the compatibility of the model, ArcMap 10.7 was used with ArcSWAT, an interface in ArcGIS. All the spatial data sets used in the study were projected to a uniform UTM 35 south and WGS84 datum. This was done to meet the requirements of ArcSWAT of using the same projection to avoid mismatch of data sets during processing to prevent crushing of the model.

A 30 m DEM of South Africa, updated soil, and land-use data were projected in ArcGIS and then linked with the SWAT model. The input data were created in a database format for the SWAT model to read the data. In terms of percentages, the slope represents the difference in elevation between two points. The DEM file was converted to polygons so that areas that are covered by slopes are identified and classified. The slope was created in each sub-basin choosing the number of classes and setting them manually. The selected classes were set as the input raster and then reclassified so that the areas with high or low slopes were grouped together into a single class. The slope was then calculated, and the most and least dominant slope types were identified. To get the best model results, 72 land uses were

grouped together to produce 6 classes that are compatible with the SWAT model. Those with the same characteristics, for example, rivers and wetlands, were grouped together to give a single land use which is presented as water (WATR).

According to Miller and White (1998), Breuer *et al.* (2009), USDA (2009) and Ross *et al.* (2018), soils play a key role in the global hydrological cycle by regulating moisture infiltration and groundwater recharge, which eventually influences lateral water transport and resulting runoff capacity. Recently, ecologists, hydrologists, and soil scientists have grown interest in knowing the soil's hydraulic properties which are crucial to parameterization of a variety of empirical and physically based hydrologic models, dynamic-vegetation models, and land-surface models. The soil data of the study area were generated using land type maps and the USDA soil texture diagram was used to determine the midpoint values of sand, silt, and clay for each of the soil texture classes. The computed sum of the sand, silt, and clay fractions must be 100%. To make the results representative of the actual soil components, the sand, silt, and clay fractions were found to contain a total sum of 100% (Miller and White, 1998). As a result, soils were grouped into four hydrological soil groups (HSGs) to predict the runoff potential (USDA, 2009) presented in Table 3. 2 below.

Table 3. 2: Properties of the HSG soil types.

HSG soil type	Runoff	%sand	%clay
HSG-A	Low	>90%	<10%
HSG-B	Moderately low	50 – 90%	10 – 20%
HSG-C	Moderately high	<50%	20 – 40%
HSG-D	High	<50%	>40%

After projecting the DEM, soil and land-use data, it was imported into ArcSWAT. An ArcSWAT project was created wherein the DEM was used to delineate the watershed together with the river shapefile to create streams in the study area. The 30 m DEM, land use, soil map, and slope data in a grid format were imported into the SWAT model to obtain a combination of exceptional results of land use, soil, and slope. When undergoing the simulation process, catchment delineation was established as the first procedure.

To eliminate minor classes of soil, slope, land use and multiple HRU's, a 10% threshold was set. Weather station meteorological data were also imported into the model as recommended in the SWAT user manual. Time series of hydrometeorological data were used as input data into the hydrological model to simulate the impact of hydrology on water availability for irrigation in the study area. Figure 3. 2 shows a workflow diagram for ArcSWAT model setup and run.

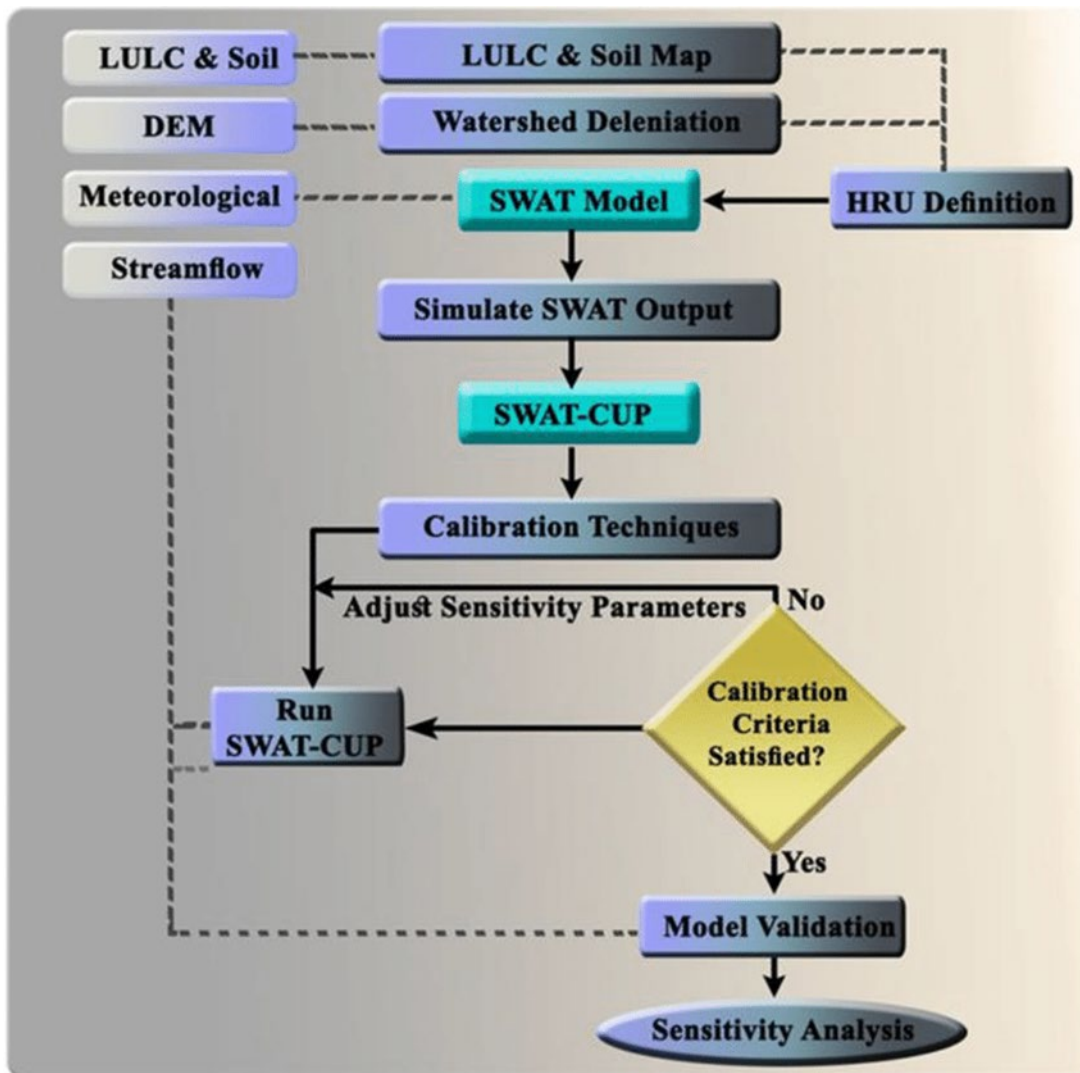


Figure 3. 2: Workflow diagram for ArcSWAT model setup and run (Shelton, 2021).

➤ Parameter sensitivity analysis

Parameter sensitivity analysis is a crucial aspect of model creation, and it entails an in-depth assessment of input parameters to improve model validation and offer direction for future research (Khalid *et al.* 2016). According to Mutenyo *et al.* (2015), SWAT requires sensitivity study of the most sensitive parameters for a specific catchment prior to calibration and

validation processes. Catchment characteristics and processes are influenced by different input parameters, and it is important to perform parameter sensitivity analysis of the hydrological model (Gyamfi *et al.*, 2016).

To determine the most sensitive parameters that have a greater impact on streamflow, a sensitivity analysis was performed using the SWAT-CUP with the SPE program. The global sensitivity analysis technique was utilised to determine the most sensitive parameters in the current study. According to Arnold *et al.* (2012a), the sensitivity of one parameter in relation to other parameters under examination is considered in a global sensitivity analysis. Using Latin hypercube regression analysis, the global sensitivity of surface runoff parameters was estimated, and the lowest and maximum ranges of parameters were then fitted for calibration using the SWAT-CUP SPE uncertainty approach. During calibration, the parameters were ordered according to their model sensitivity (Abbaspour, 2012). Table 3. 3 shows the description of parameters that were used for sensitivity analysis.

Table 3. 3: Description of parameters used.

Parameter name	Description
CN2.mgt	SCS runoff curve number.
ESCO.hru	Soil evaporation compensation factor
SOL-K(..).sol	Soil conductivity (mm h^{-1}).
GWQMN.gw	The threshold depth of water in the shallow aquifer required for return flow to occur ($\text{mm H}_2\text{O}$).mm
REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” to occur (mm).
GW-REVAP.gw	Groundwater revap coefficient.
SLSUBBSN.hru	Slope length of the basin
SOL-AWC (..).sol	Soil available water storage capacity ($\text{mm H}_2\text{O}/\text{mm soil}$).
SURLAG.bsn	Surface runoff routing.
ALPHA-BF.gw	Baseflow alpha factor (day).
GW-DELAY.gw	Groundwater delay (day).
MSK-COL1	Calibration coefficient used to control impact of the storage time constant for normal flow.

SHALLST.gw	Initial depth of water in the shallow aquifer (mm.H ₂ O)
RCHRG_DP.gw	Deep aquifer percolation function.

➤ Model calibration, validation and evaluation of performance

The model was run for a period of 27 years from 1987 – 2014, with the initial 4 years from 1987 – 1990 used as a warm-up period for a watershed of 529,14 km² on a monthly output timestep. The water levels for the period 1932/10/04 to 1946/12/28 were obtained from a gauging station A8H001 which is located at the outlet of A80B. Due to limited observed data, the comparison between simulated and observed flow was done from 1991 – 2009. Model calibration was done from 1991 – 2000 while model validation was done for the period 2001 - 2009. The 2010 to 2014 period was excluded because the streamflow data that were used were recorded until the year 2009. Based on the availability as well as the quality of existing datasets in the watershed, both manual and automatic calibration procedures were the most viable in this study. Automatic calibration was done to improve the hydrograph patterns and model performance measures. Manual calibration was done following a multistep procedure recommended by Neitsch *et al.* (2002) and van Liew *et al.* (2005). The catchment was calibrated at an outlet point located at sub-catchment A80B. On a monthly basis, preliminary calibration was performed to identify the order of magnitude of all parameters to replicate proper runoff volumes and seasonal changes/differences.

Automatic calibration was done using SWAT-CUP, which includes automated and semi-automated model calibration procedures. The following steps were followed during calibration using SWAT-CUP: The first step was to create initial or default SWAT input parameters (as generated by ArcSWAT) and SWAT-CUP input files. The model was run with the default parameters and the simulated and observed variables for the duration of the data in step 2. In step 3, the entire model period was divided into calibration and validation periods, depending on the previous step, making sure that both have a similar number of wet and dry years and average water balances. In step 4, the most sensitive parameters to the observed values of interest were identified. In step 5, the initial uncertain range (typically 20% to 30%) was assigned to each parameter globally, implying that the parameters should be scaled in the same way for each HRU. In step 6, the SWAT-CUP SPE software was run 300 to 500 times, and the output for the outlet was examined. The second last step was to do the global sensitivity analysis and examine the results. It is in this stage where the P-factor and p-value t-statistic were used to eliminate non-sensitive parameters from the calibration process.

Lastly, after observing model performance in step 6, parameters were regionalised. This is where modifications to all the parameters that were sensitive to streamflow in the study area occurred to obtain realistic baseflow and match the location of the simulated peaks to the observed ones. This procedure was adopted from a study by Rouholahnejad *et al.* (2012).

Validation of streamflow, which was the component of interest, was done following calibration phase. Model validation is the process of verifying that a certain site-specific model can provide simulations that are sufficiently accurate; however, model validation can vary depending on the objectives of the project (Refsgaard, 1997). Using parameters that were established during the calibration process, a model was run for validation, and the predictions were compared to observed data that were not utilised for calibration. Observational data comprising wet, average, and dry years were used in the calibration and validation of the model. Lastly, the SWAT model's performance was evaluated based on measured monthly streamflow data. Model performance was done focusing on measures of performance which included R^2 , NSE, and PBIAS.

3.4.2. Estimation of inflows into Raliphaswa weir

Inflows into the Raliphaswa weir were estimated using ArcSWAT, an interphase of ArcGIS software. Using a calibrated and validated SWAT model, a reach in which the weir is located and then the inflows were simulated. The flow into the irrigation schemes was done following the procedure outlined in the report by Ndiritu *et al.* (2023). To determine the inflows into the irrigation schemes, the simulated flows from the SWAT model were used with crop water requirements obtained by the Hargreaves method, assuming the dominant maize crop and an irrigation area of 171 ha. The simulated flows from the SWAT model were also compared with the observed flows from station A8H011 downstream of Mutshedzi Dam. This was done to see how the SWAT model performed when simulating flows at the catchment outlet, which is downstream of the dam.

3.4.3. Estimation of crop water requirements

The crop water requirements were estimated using the crop water data from Allen *et al.*, (1998) and data from farmers. All these were incorporated together and inserted into the crop coefficient (K_c) equation with the Hargreaves evapotranspiration equation (ET_o). The Hargreaves equation is the second-ranked temperature-based method that is used as a representative expression for potential evapotranspiration (Hargreaves, 1981; Hargreaves and Samani, 1985) to determine crop water requirements (ET_c). In this study, the Hargreaves

equation was used to estimate reference evapotranspiration (ET_o) due to limitations in available climate data. The Penman-Monteith method, while widely regarded as the most physically based and accurate method recommended by the FAO, requires a full set of climatic variables including solar radiation, relative humidity, and wind speed (Allen et al., 1998). These variables were not consistently available for the study area from the South African Weather Services (SAWS).

The Hargreaves equation offers a practical alternative in such data-scarce environments, as it relies only on maximum and minimum temperature and extraterrestrial radiation - making it more suitable where climate data infrastructure is limited. The method has been shown to produce reasonably accurate ET_o estimates in semi-arid and tropical climates when calibrated to local conditions (Tabari et al., 2013; Odhiambo et al., 2021). Given the study's location in a semi-arid region with limited meteorological coverage, this method was deemed appropriate for initial planning and estimation of crop water requirements.

This equation was used with the K_c values which were computed by the CROPWAT model to estimate the daily crop water requirements of different crops in the study area. The area under irrigation, together with the total crop planted per acre, was used to determine the total crop water required by maize, ground nuts, sweet potato, and green beans per growing season. To get a clear indication of how much water each crop requires, graphs were plotted for a single growing season.

Moreover, several studies across Southern Africa have successfully used the Hargreaves method in hydrological and irrigation assessments when full climatic data were unavailable (Tesfahunegn et al., 2019; Woldesenbet et al., 2017). Although less robust than the Penman-Monteith method, the Hargreaves equation provided a reliable basis for modelling under the constraints of the available data.

3.4.4. Comparison of inflows and irrigation water requirements

The comparison was done based on computed crop water requirements, the area under irrigation, and the simulated inflows, considering a reasonable conveyance efficiency of 60%. Conveyance efficiency (CE) refers to how effectively the delivery system can provide the required amount of water. It is calculated by dividing the water delivered to the irrigated area by the total water supplied or diverted from the source, which could be reservoirs, rivers, or

groundwater. It measures how much water reaches the destination compared to how much is lost along the way due to things like leaks, evaporation, or spills (Haymale *et al.*, 2020; Eisenhauer *et al.*, 2021; Doorenbos and Pruitt, 1997). Therefore, high conveyance efficiency means more water makes it to its destination without being wasted. According to literature studies, conveyance efficiency for surface irrigation is 50% - 70% (Anjum *et al.*, 2023) and 45% - 60% Ley and Leib (2003). In this study, conveyance efficiency was assumed at 60%. This is because it is the average value stated in literature. To get the quantity of water conveyed to the farm, the conveyance efficiency was multiplied by the estimated water availability. Then the total amount of water conveyed into the irrigation scheme was compared with the estimated crop water requirements to know if the available water can meet irrigation water requirements.

3.4.5. Recommendation of types of crops that can be planted at the schemes

The recommendation of crops that can be planted in the schemes was made considering the available water, the water requirements of such crops, and the climate of the study area. Given that the study area is climatically dynamic, it was important to also consider the climate dynamics when recommending the types of crops that can be planted, as this has an influence on plant growth.

3.4.6. Missing data

In hydrological studies such as this one, the availability of high-quality, continuous hydrometeorological data is essential for producing reliable model simulations and supporting evidence-based decision-making (Arnold *et al.*, 2012; Beven, 2001). However, during this study, it was noted that key datasets - particularly streamflow and rainfall records were either partially or completely missing for certain time periods. These data gaps were primarily due to equipment failure, a lack of maintenance, and past flood events that damaged monitoring infrastructure in the study area (DWA, 2013).

Missing daily rainfall and temperature values were supplemented using the SWAT model's internal weather generator (WGEN), which interpolates data using long-term statistics from nearby meteorological stations (Neitsch *et al.*, 2011). For reference evapotranspiration (ET_o), the Hargreaves equation was employed instead of the more data-intensive Penman-Monteith method, as it requires only daily minimum and maximum temperatures, which were more complete and consistently available (Droogers and Allen, 2002).

While these gap-filling methods enabled the model to execute and generate usable outputs, it is acknowledged that the use of interpolated or estimated data introduces a degree of uncertainty, particularly during model calibration and validation. Such uncertainty may affect the precision of simulated streamflow and, by extension, the assessment of water availability for irrigation planning (Moriasi et al., 2007; Zhang et al., 2008).

CHAPTER FOUR: RESULTS

4.1. Preamble

This chapter focuses on discussions of the results of hydrological modelling for estimating water availability for irrigation supply in selected smallholder irrigation schemes in the Nzhelele area. These include results on the estimation of water availability for irrigation supply in selected smallholder irrigation schemes, results on hydrological (SWAT) model setup, calibration, and validation for estimating inflows into Mandiwana, Mamuhohi, and Raliphaswa smallholder irrigation schemes. It also includes results on the estimation of irrigation water requirements (crop water requirements) for Mandiwana, Mamuhohi, and Raliphaswa smallholder irrigation schemes.

4.2. Hydrological modelling and inflows results

4.2.1. Results for sensitivity analysis for calibrated model

Table 4. 1 displays the calibration technique utilised, the limits for the calibration interval of the parameters (Pinto *et al.*, 2013; Pereira *et al.*, 2016; Almeida *et al.*, 2018), and the calibrated value for each parameter. In this study, 14 parameters were found to be sensitive to streamflow and these include parameters responsible for surface runoff (CN2, ESCO and SURLAG), baseflow (GWQMN, REVAPMN, GW-REVP, RCHRG-DP, GW-DELAY, ALPHA-BF, SHALLST), soil parameters (SOIL-K, SOL-AWC) and other parameters MSK- COL1 which is used to control the impact of storage time constant for normal flow.

In Table 4. 1, parameters were ranked according to their sensitivity to streamflow in the study area. Table 4. 1 also shows the min and max value range used during sensitivity analysis. Different parameters are displayed in Figure 4. 1a and Figure 4. 2b. The primary objective of dot plots is to display the distribution of the sampling points and to provide an understanding of parameter sensitivity. When examining the scatter plots produced during calibration, it was found that most parameters showed significant variation in their values, with CN2, ESCO, SOL-K, GWQMN and REVAPMN being more distinct, displaying higher variance than other parameters, signifying that those other parameters were the predominant source of streamflow uncertainty in the Nzhelele area. The original SCS runoff curve number for moisture condition II (CN2), the soil conductivity (SOL_K), and the soil evaporation compensation factor (ESCO) were all changed to increase the flow peaks. To lower the baseflow prediction and achieve the optimal match of flows in the hydrographs and attain the appropriate statistical parameters for calibration, slight adjustments were made to the

threshold depth of water in the shallow aquifer required for the base flow to occur (GWQMN) have been made. Similar graphical and statistical SWAT calibration studies have been described in the literature, including studies that were done in semi-arid regions have been published in the literature (Meaurio *et al.*, 2015; Molina-Navarro *et al.*, 2016; Moriasi *et al.*, 2007). Most of these studies utilised R^2 and NSE (some also used PBIAS) to evaluate model prediction ability, and they all agreed that R^2 and NSE of 0.5 to 0.74 (and a PBIAS of +/-25) are acceptable calibration efforts.

Table 4. 1: Calibration method used, initial min and max adjustment intervals and the calibrated value for each parameter used.

Ranking	Parameter name	Units	Method	Default values	Range		Calibrated value
					Initial min value	Initial max value	
1	CN2.mgt	Dimensionless	Relative	35	1	90	8.955
2	ESCO.hru	Dimensionless	Replace	1	-0.980	1	-0.890
3	SOL-K(..).sol	mm.h ⁻¹	Relative	0	-0.800	0.800	0.436
4	GWQMN.gw	mm.H ₂ O	Replace	0	-10	300	201.364
5	REVAPMN.gw	Mm	Replace	0	50	10000	6834.091
6	GW-REVAP.gw	Dimensionless	Replace	0.02	0.002	10	3.410
7	SLSUBBSN.hru	Meters	Replace	10	-0.500	2	1.205
8	SOL-AWC (..).sol	mm.H ₂ O/mm soil	Relative	0	-10	-0.010	-7.730
9	SURLAG.bsn	Dimensionless	Replace	0.05	0.980	22	9.580
10	ALPHA-BF.gw	Day	Replace	1	0.050	0.650	0.623
11	GW-DELAY.gw	Day	Replace	0	-0.150	0.480	-0.121
12	MSK-COL1	Dimensionless	Replace	10	1.330	8.150	1.640
13	SHALLST.gw	mm.H ₂ O	Replace	0	500	10000	6113.636
14	RCHRG_DP.gw	Dimensionless	Replace	0	0.010	0.510	0.124

*Relative(r) is reported when a percentage relative change is applied to default values.

**Replace(v) is reported when default values are replaced by the calibrated value.

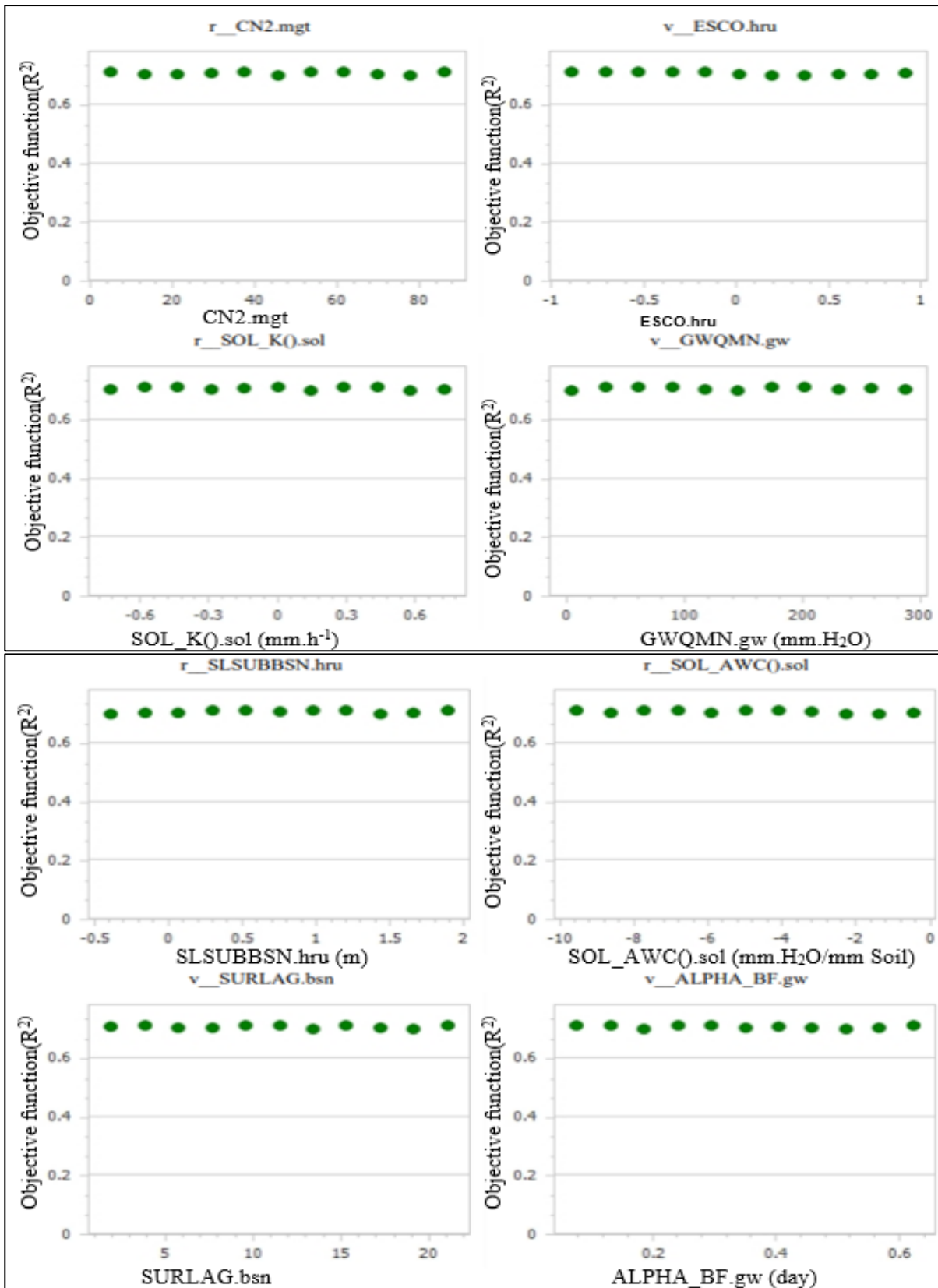


Figure 4. 1a: Dotty scatter plots showing sensitivity of parameters to streamflow in regard to R^2 objective function.

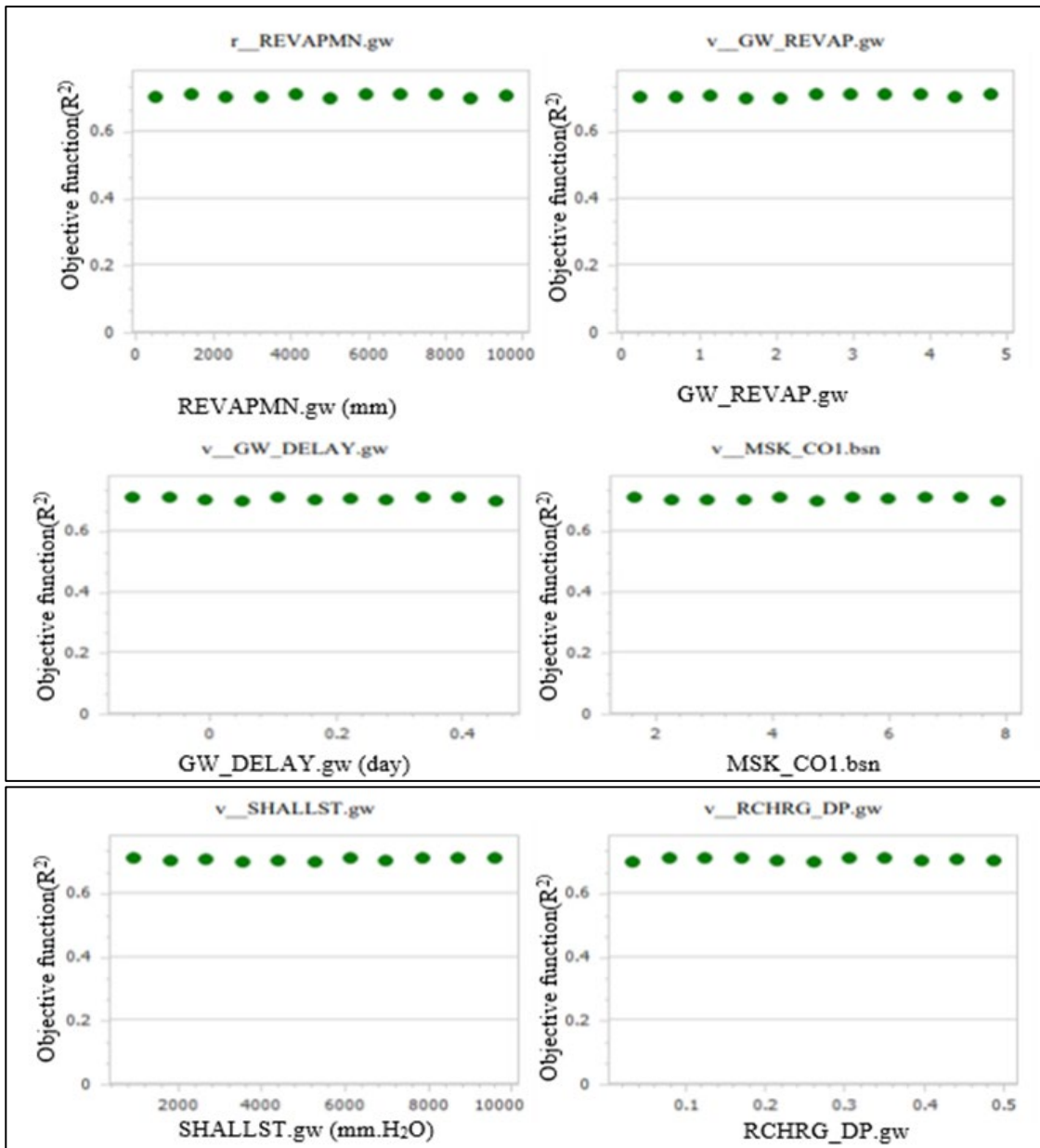


Figure 4. 2b: Dotty scatter plots showing sensitivity of parameters to streamflow in regard to R^2 objective function.

4.2.2. Results on catchment delineation, slope, soils and HRUs

The catchment of the study area was delineated using a projected DEM which is a grid layer of square cells with accompanying elevation values, shown in Figure 4. 3. The catchment consists of a river reach, longest path, watershed, and drainage basins. All these factors were used in drainage network identification, estimation of elevation, slope, watershed, and terrain stability of the catchment. The topography of the area distribution is indicated by the lowest and the highest elevation 649 m and 1599 m, respectively. High DEM value of 1599 indicates high slope areas with less or no agricultural activities taking place. According to Matinfar *et al.* (2011), DEMs provide a significant role in soil and agricultural enhancement which leads

to accuracy characterisation. The variation in DEM has a significant impact on hydrology within a study area and it is one of the useful tools to consider during planning for different activities such as agriculture and community development. Harrower (2010) emphasised the use of DEM as an important source of data in GIS and is required for hydrological modeling, which also includes the modeling of the current study.

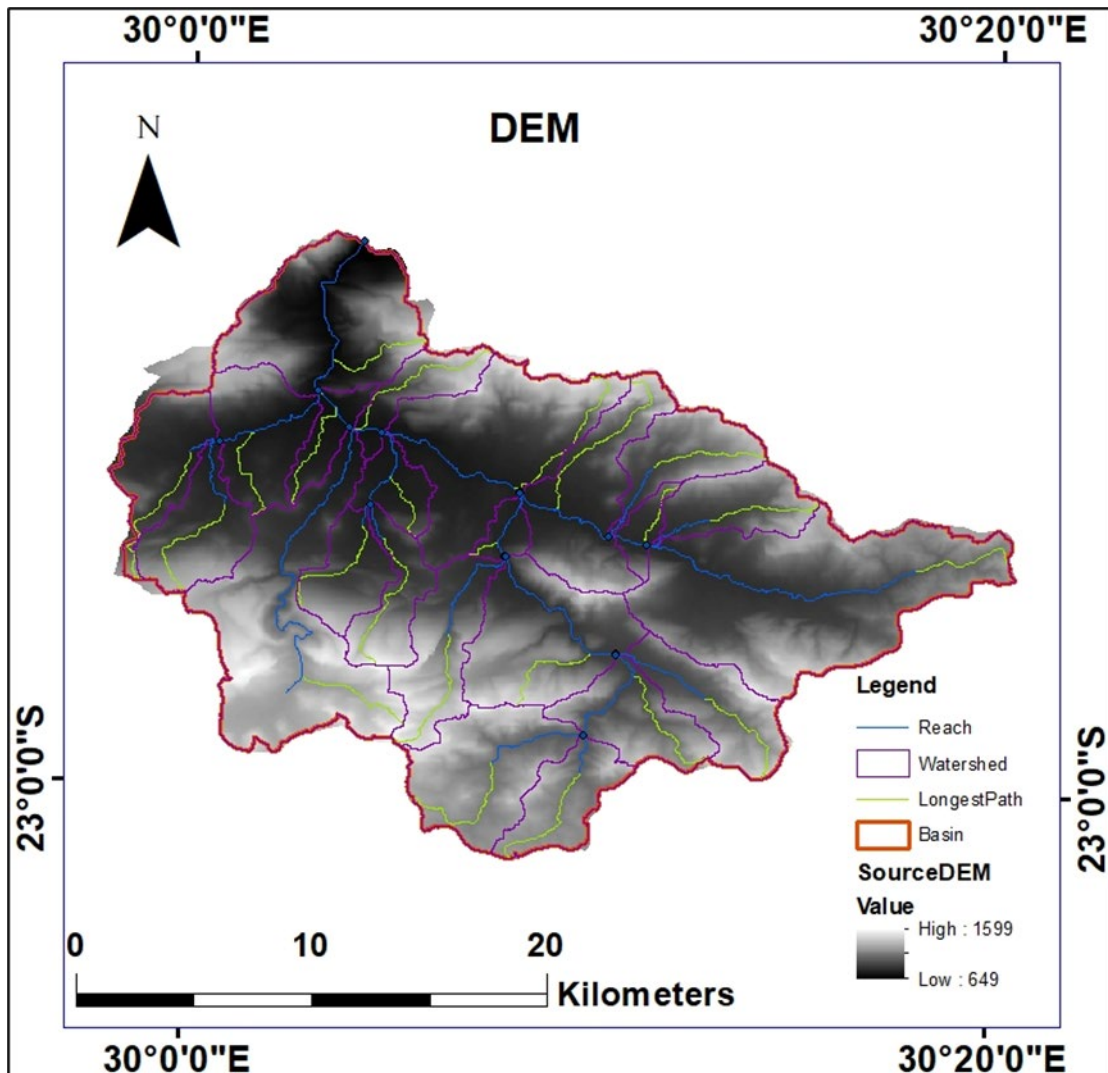


Figure 4. 3: DEM derived from the SRTM dataset of 2013.

In the study area, the most dominant slope ranged between 0 - 10 with 27.75 % and the least dominant slope was found to range between 50 - 99 with 8.03 % (Figure 4. 4). This means that the area is predominantly characterised by moderately gentle slopes, which are favourable for farming activities, as they are less prone to high runoff and the resulting erosion of fertile soil. Slope plays a significant role in soil fertility and crop production; this can be supported by a study done by Ma *et al.* (2019). Figure 4. 4 shows a slope map of the study area.

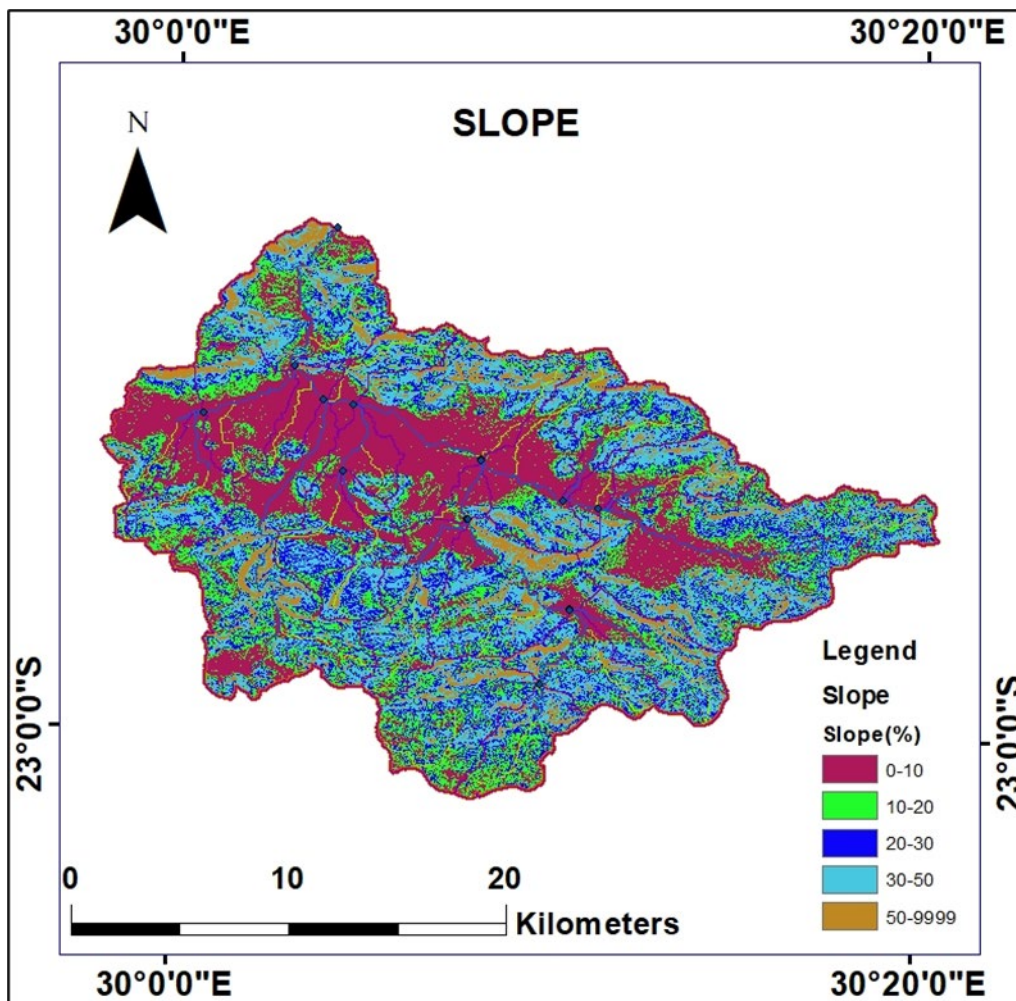


Figure 4. 4: Slope calculated from the 2013 DEM.

Table 4. 2 shows the LULC classification, the SWAT land-use code, and the area each land use covers. Figure 4. 5 shows a map presentation of the land-use classes presented in Table 4. 2 LULC spatial distribution of the catchment was based on 6 classes. The study area was divided into 23 Sub-basins with the most area covered with forest – mixed (FRST) and least with Southwestern US (arid) range (SWRN). The second most dominant land-use is agricultural land-row crops (AGRR) which have an influence on infiltration and also act as a management tool or method to control runoff which may result in reduced floods events and soil erosion in the area.

Table 4. 2: LULC classification and description.

LULC classifications	SWAT land-use codes	Area (km ²)
Agricultural Land-Row Crops	AGRR	70.26
Forest-Mixed	FRST	399.55
Residential-Med/Low Density	URML	51.12
Residential-High Density	URHD	3.19
Water	WATR	5.50
Southwestern US (Arid) Range	SWRN	0.98

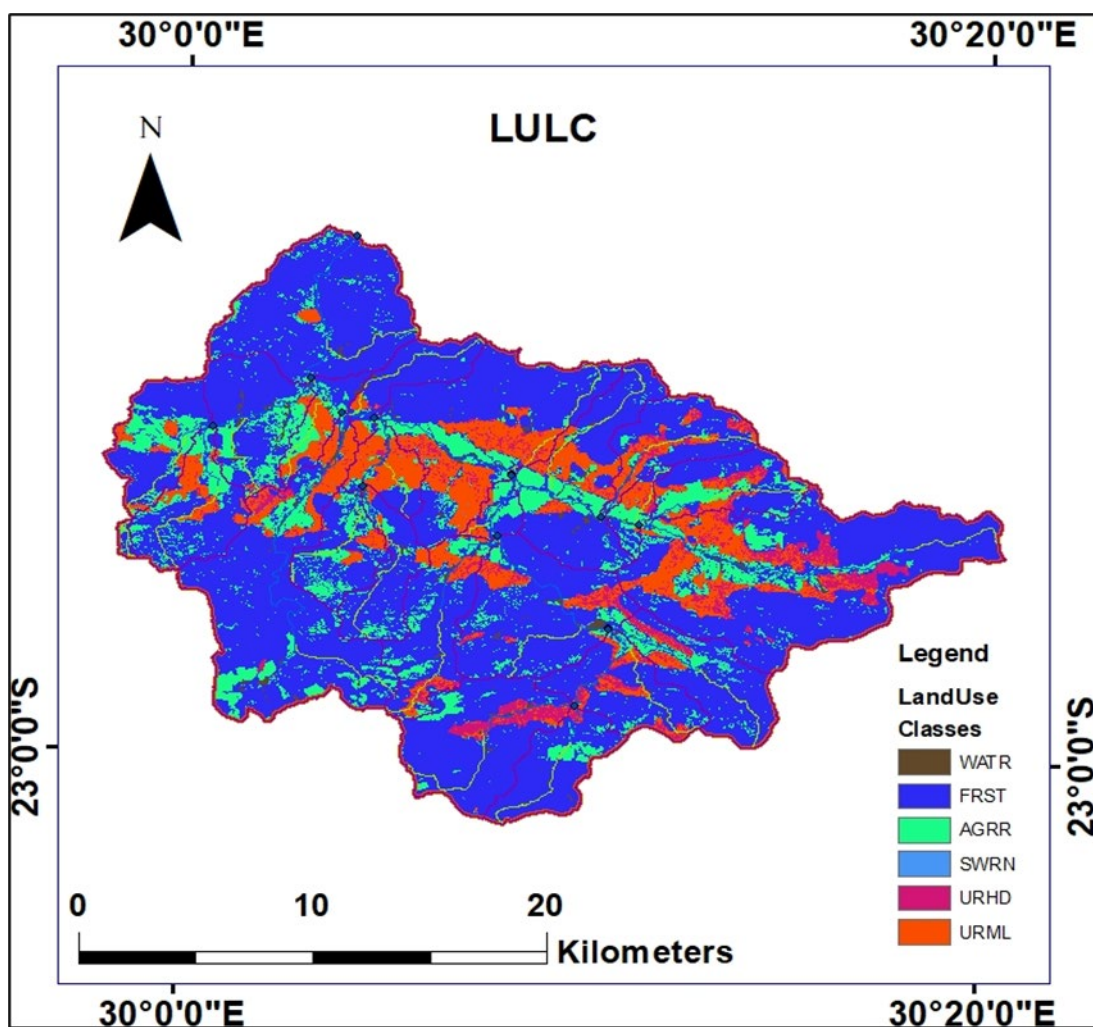


Figure 4. 5: LULC Based on the South African National Land Cover (SANLC) 2018 dataset.

From the soil data used, it was found that soils with moderately low runoff potential dominate the study area distribution (HSG-B) together with high runoff potential soils (HSG-D), followed

by moderately high runoff potential (HSG-C), and lastly, soil with low runoff potential (HSG-A) (Table 4. 3) (USDA, 2009). Figure 4. 6 shows the soil map of the study area.

Table 4. 3: Soil classifications and textural characteristics.

Soil name	Texture	Approx. Texture (%wt.)			Hydrological soil group (HSG)
		Clay	Silt	Sand	
ZA 50	Clay loam	28	29	43	C
ZA 61	Loam	19	29	52	B
ZA 70	Sandy loam	19	7	74	A
ZA 90	Sandy clay loam	19	29	53	C
ZA 91	Loam	19	29	52	B
ZA 94	Loam	19	29	52	B
ZA 96	Sandy loam	15	18	67	A
ZA 100	Clay loam	32	23	45	D
ZA 103	Clay loam	19	29	52	D
ZA 109	Sandy clay	32	23	45	D

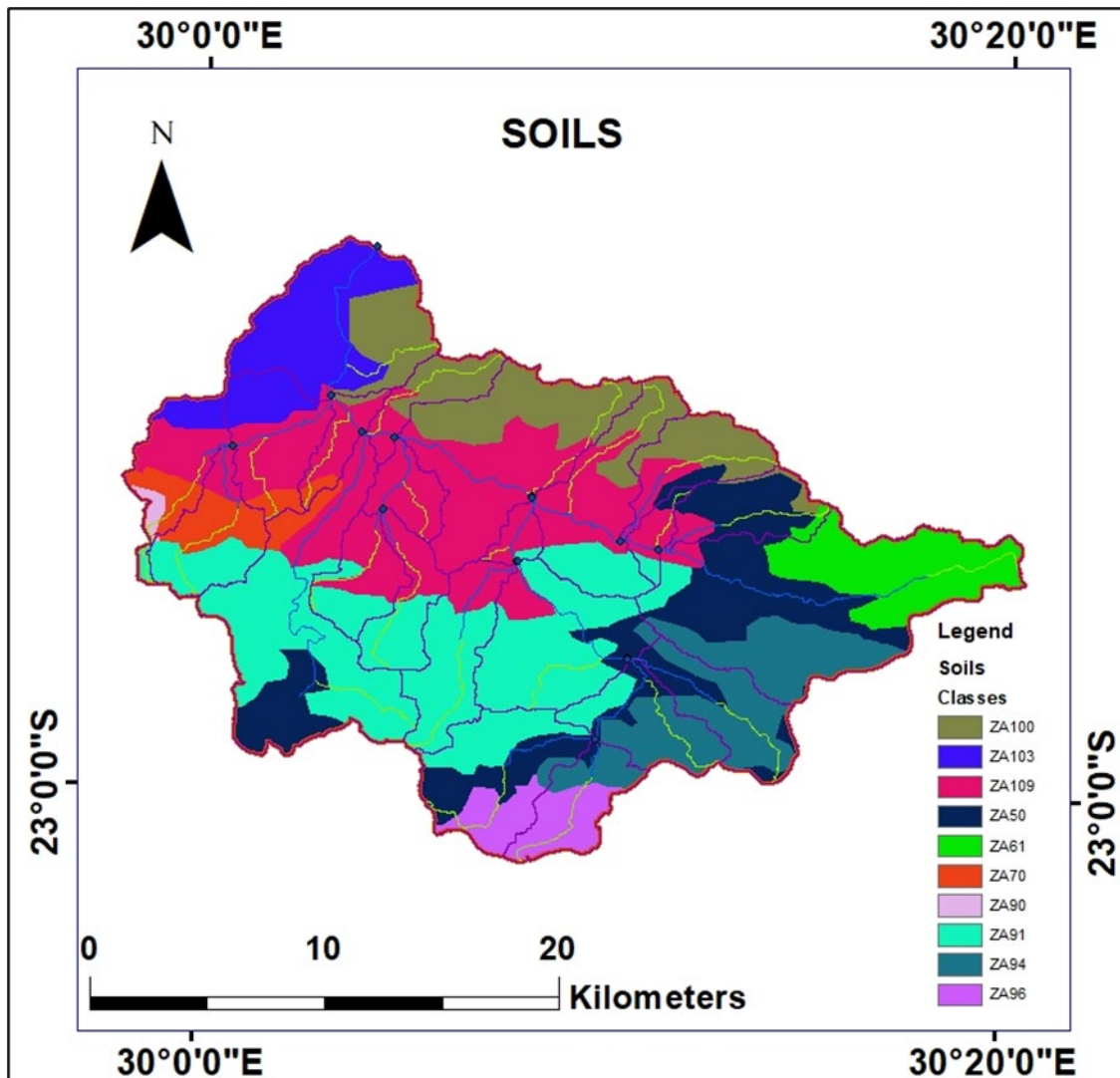


Figure 4. 6: Soil Map of the Study Area (Derived from ARC Soil Data, 2006).

Based on the combination of land use, soil types, and slope data, the model was subdivided into small areas known as hydrological response units (HRUs). A minimum threshold of 10% was used to eliminate minor land uses, soils, and slopes in each sub-basin, facilitate processing and to limit the number of HRUs in each sub-basin. This means that all the HRUs that have an area percentage with less than 10% coverage in a subbasin will be ignored by the model. This resulted in 293 HRUs for the 23 sub-basins. Figure 4. 7 shows a map of the HRUs created in the study area. When all the required data were integrated, the model was allowed to run, and the hydrological parameters were extracted.

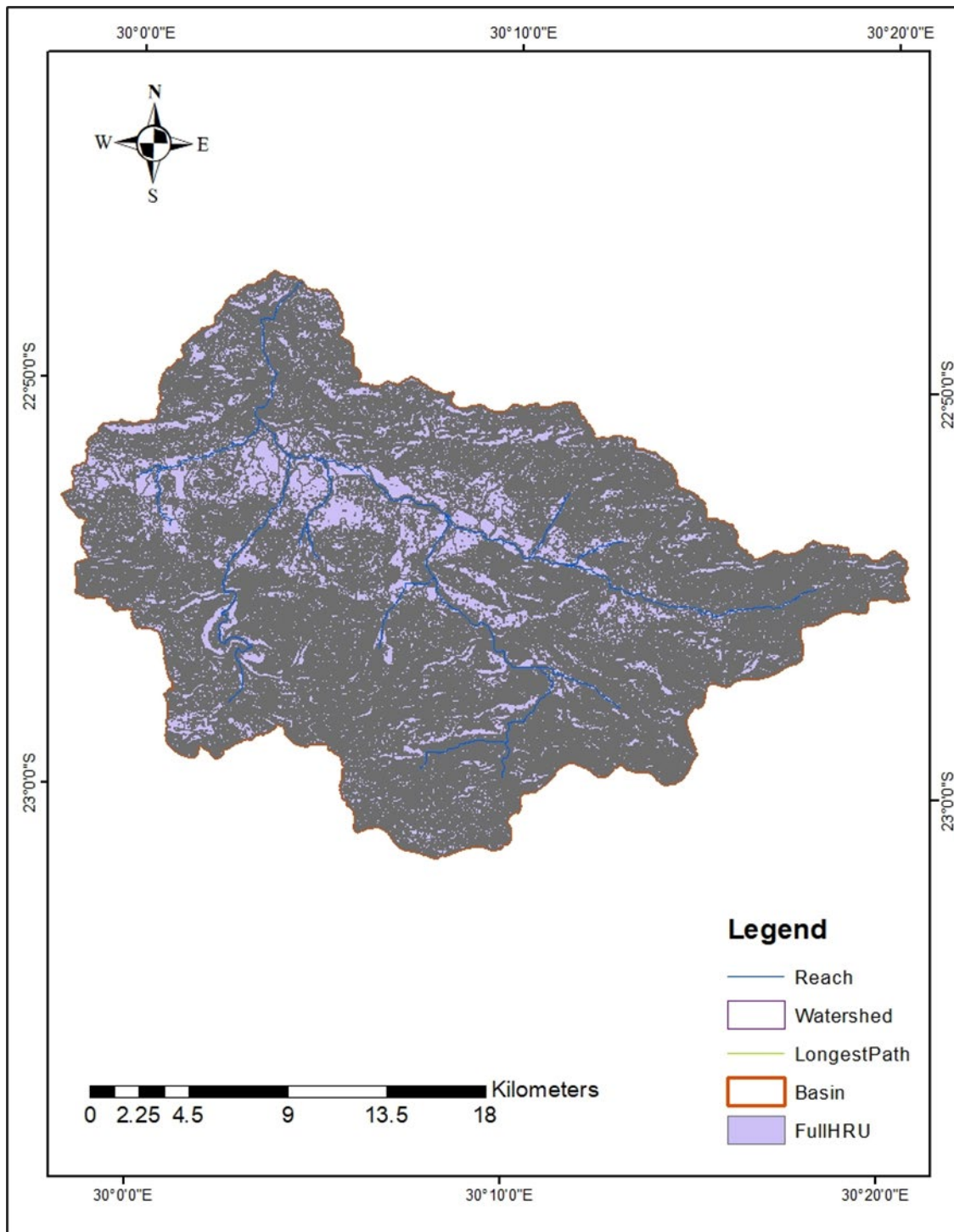


Figure 4. 7: HRU map of the study area.

The SWAT model's water balance equation was used to determine the catchment's modelled water balance components presented in Table 4. 4. Figure 4. 8 shows the modelled water balance, a simple illustration of the distribution of total annual average precipitation into different hydrologic components in the area. In SWAT modelling, precipitation is considered as the intake to the watershed unit, evapotranspiration and deep percolation as losses, and surface runoff, return flow, and lateral flow as the outflow. According to the model results, the

catchment receives around 640.9 mm of annual precipitation on average. Evapotranspiration, surface runoff, lateral flow, shallow aquifer storage, and deep aquifer recharge are all components of yearly precipitation. The results showed that 276.9 mm of rainfall was lost from the watershed due to evapotranspiration. This is the most significant water balance component, accounting for approximately 43% of total rainfall. Evapotranspiration is the water-balancing component that consumes a considerable portion of the catchment's rainfall, and it accounts for about 43% of the water. From Figure 4. 8, a high average curve number of 89.99 was recorded, meaning that the area is prone to high runoff, which could result in flooding. This can also be supported by the flooding event that took place during this project which occurred in the beginning of the year 2021 which led to the damage of the three smallholder irrigation schemes.

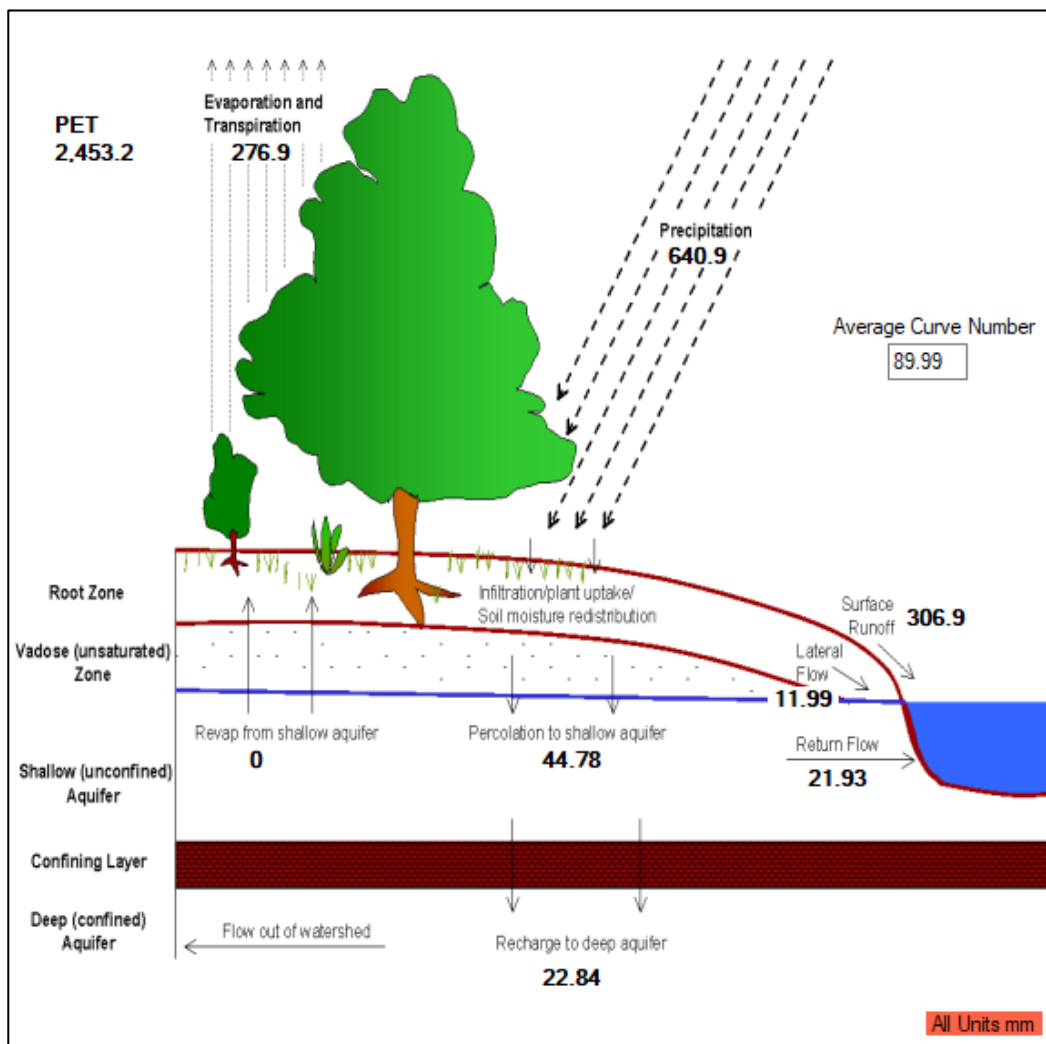


Figure 4. 8: Modelled water balance of the study area.

Table 4. 4: Hydrological water balance ratio of the study area.

Parameter	Ratio
Precipitation	0.53
Baseflow	0.1
Surface run-off	0.9
Percolation	0.07
Deep recharge	0.04
ET	0.43

4.2.3. Results on model calibration and validation

Figure 4. 9 shows the graphical plot of observed and simulated flows for calibration run. From the figures presented, simulated flow mimicked the observed flow patterns in most cases though in some cases there were differences in flow patterns. During the calibration run, underestimation was observed in December 1992, and overestimation was observed in February 1997, January 1998, and February 2000, and the model was well estimated in 1991, 1993, 1994, 1995, 1996, and also in 1999.

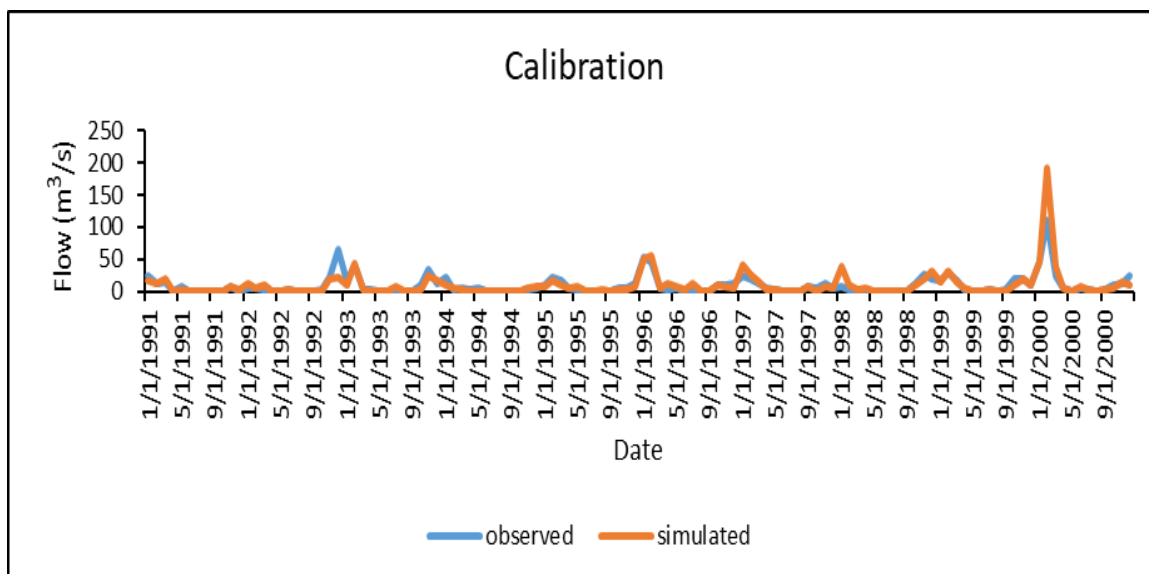


Figure 4. 9: Graphical plot for observed and simulated flows for calibration run.

Singh et al. (2005) found that the SWAT model overestimated streamflow during drought years by 39 - 49% while underestimating flow during the wettest year by 14 - 7.2% and this was due to the presence of tile drains in the watershed in Iroquois River watershed in Illinois and Indiana. Arnold et al. (2000) found out that the Upper Mississippi River basin's Soil and Water Assessment Tool (SWAT) underestimated spring peaks and overestimated fall

streamflow, which they attributed to seasonal variation in ET and soil moisture condition, as well as snowmelt simulation. Govender and Everson (2005) found that the SWAT model performed better in average and dry years than in wet years on South Africa's east coast due to inaccurately simulated evaporation.

There was a strong positive correlation between observed and simulated streamflow, this is because when observed streamflow increases, the simulated streamflow also increases as seen in Figure 4. 10, which shows the scatter plots for observed and simulated flow for calibration run. Few outliers were present during the calibration run which constitutes a strong correlation between observed and simulated streamflow. The calibration graphical and scatter plot results for this study agree with those obtained by Serur and Adi (2022) where the best-fit line's correlation coefficient ranged from 0.64 – 0.80. The study is compared to the current study because it focused on multi-site calibration of SWAT hydrological model. The model was automatically calibrated using SWAT-CUP and also, the majority of parameters that were chosen were also applied in the current study.

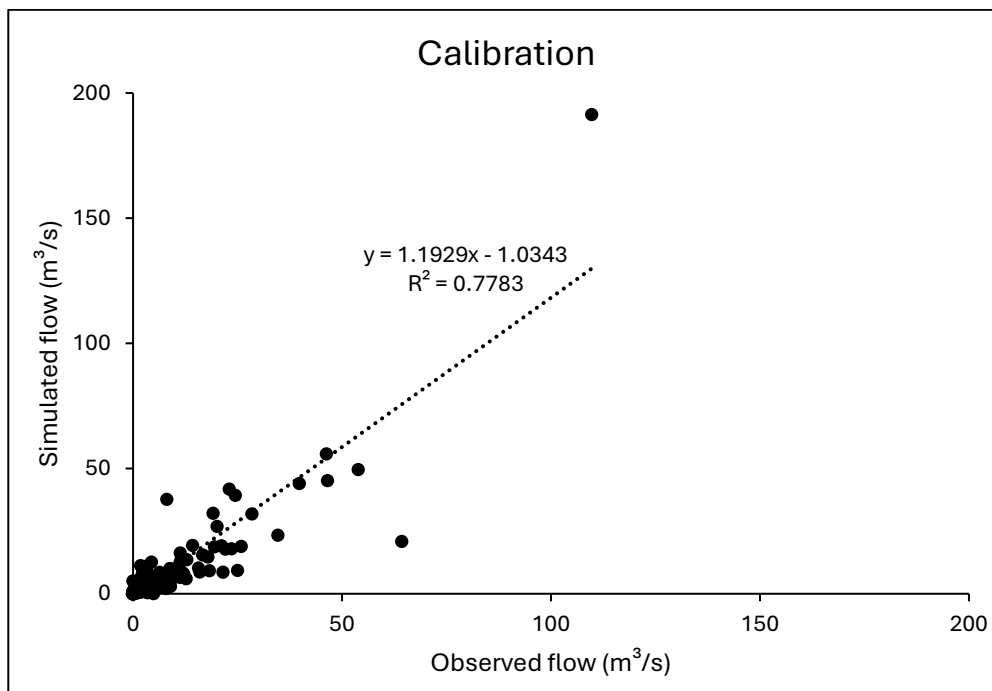


Figure 4. 10: Scatter plot for observed and simulated flows for calibration run.

Figure 4. 11 shows graphical plot for observed and simulated flows for validation run of the SWAT model. During validation run, model underestimation was observed mostly in the periods February 2001, March and November 2003, January, August, October and December 2004, March 2005, November 2006, September, November and December 2007, January and November 2009, model overestimation during August 2001, December 2004, February

2006, January 2007 and March 2009 and the model was well estimated during December 2001, June 2003, March 2004, March 2007 and June 2009.

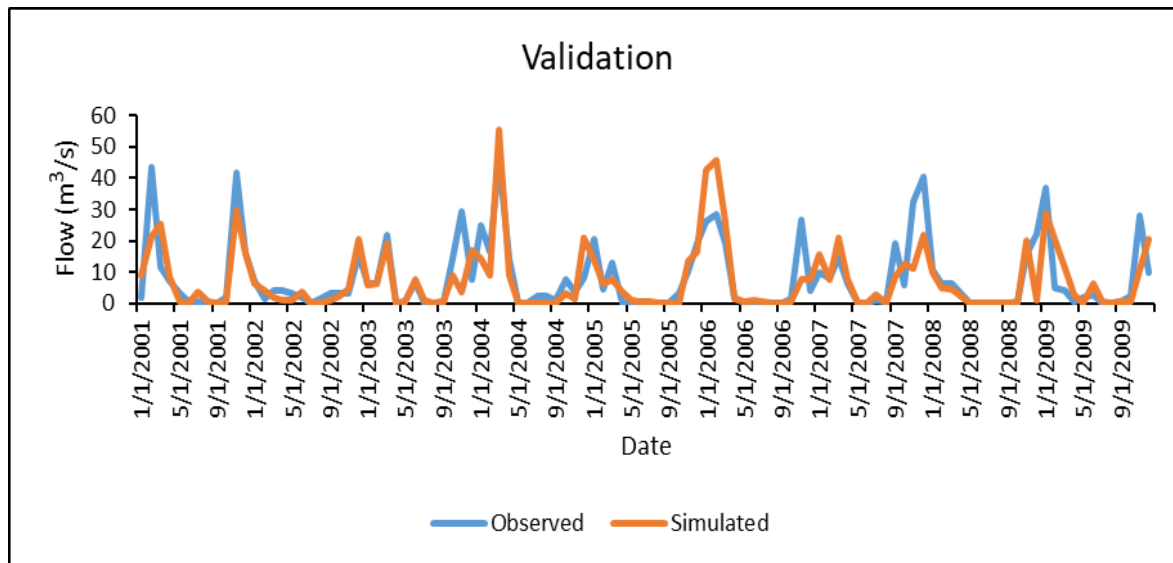


Figure 4. 11: Graphical plot for observed and simulated flows for validation run.

A strong correlation was observed for the validation, with more outliers being seen during validation period as compared to calibration period, which also constitutes to the medium correlation observed, as seen in Figure 4. 12. The validation scatter plot results for this study were found to be slightly like that of Thavhana *et al.* (2019) where the best-fit lines correlation coefficient ranged from 0.34 – 0.63 for different flow stations. The results were compared to those of the current study since the SWAT model was used in simulating runoff in the Luvuvhu River Catchment of the Limpopo Province, which is in the vicinity of the current study area.

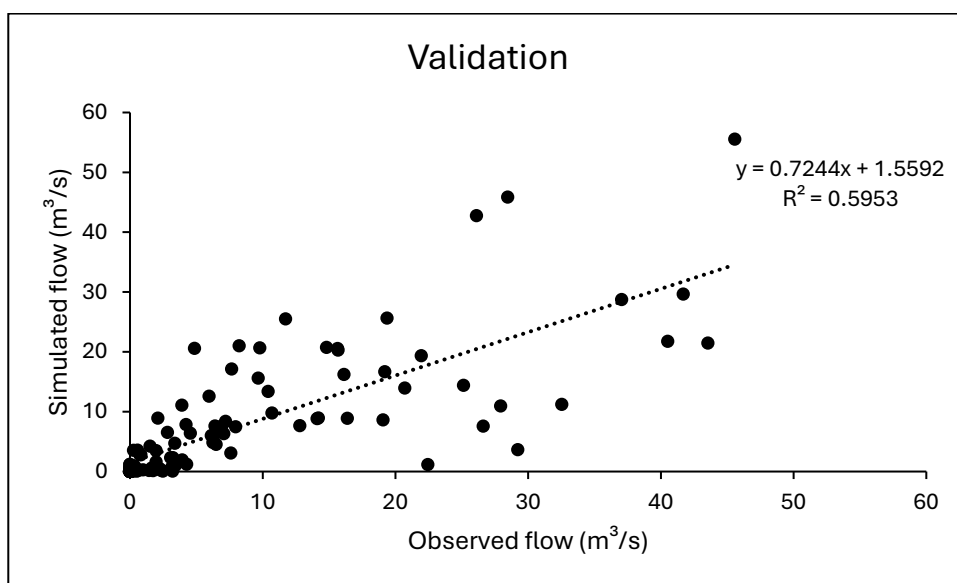


Figure 4. 12: Scatter plot for observed and simulated flows for validation run.

There are several reasons for the SWAT model to overestimate and underestimate the streamflow. These include data gaps and limited of the data that is used in building and calibrating the SWAT model (the absence or availability or little observable data) (Mengistu *et al.*, 2019), generalised land use and soil data, unaccounted water abstractions, parameter generalisation, the uncertainty involved with daily flow simulations due to variations in how the model forecasts flow and how observations are done to acquire observed flows (Obiero *et al.*, 2019) and the changes caused by the land-use activities and the underlying soils which accounted for during model setup.

According to Romanowicz *et al.* (2005), the SWAT model is particularly sensitive to soil and land use data quality. Graphical plots of the observed versus simulated streamflow have been presented in different studies including a study by Mengistu *et al.*, (2019), Obiero *et al.* (2019), Thavhana *et al.* (2018) and Moriasi *et al.* (2007), Mbungu and Kashaigili (2017) and Yuan *et al.* (2015). In all these studies, there was overestimation and underestimation of some of the observed flows.

The relationship between simulated and observed streamflow data is of crucial importance because it helps in determining the model's performance. The findings of the model performance indicators are provided in Table 4.5 for the model performance evaluation. The key goal function was the coefficient of determination (R^2). The Nash-Sutcliffe coefficient efficiency (NSE) and the percent bias (PBIAS) were also chosen as performance indicators. As seen from the findings, all the performance indicators for both the calibration and validation periods are positive and indicate a good model result.

Table 4. 5: Table showing measures of statistical performance.

	R^2	NSE	PBIAS
Calibration	0.78	0.56	+7.7%
Validation	0.60	0.56	-8.3%

The values of R^2 , NSE, and PBIAS for the calibration period were 0.78, 0.56, and +7.7%, respectively. The values of R^2 , NSE and PBIAS for the validation period were 0.60, 0.56 and -8.3%. During the calibration period, the model overestimated streamflow and underestimated it during the validation period, as shown by the positive and negative values of PBIAS. Different studies on using conducted the SWAT model have been conducted, and it has been advised that for a model to be satisfactory, the values of R^2 , NSE should be greater than 0.5 and that PBIAS should range between +/-25% Moriasi *et al.* (2007) and Van

Liew *et al.* (2007). The results from this study for R^2 are comparable to those of Mengistu *et al.* (2019), Thavhana *et al.* (2018) and Tessema *et al.* (2021) and the preliminary results obtained by Obiero *et al.* (2019). In these studies, R^2 values of greater than 0.5 were obtained during calibration and validation periods. The NSE results for the current study are comparable to those of Moriasi *et al.* (2007), Mengistu *et al.* (2019), Thavhana *et al.* (2018), and Tessema *et al.* (2021), where NSE values of greater than 0.5 were recorded. The obtained PBIAS results agree with those of Moriasi *et al.* (2007), Thavhana *et al.* (2018), and Mengistu *et al.* (2019) for the calibration period. However, other stations recorded poor PBIAS values during validation in the studies by Thavhana *et al.* (2018) and Moriasi *et al.* (2007). The model performed better during the calibration period than it did during the validation period, according to a comparison of the statistical measures for the calibration and validation periods (Table 4. 5). This finding is consistent with research by Moriasi *et al.* (2007), which found that the model performed better during the calibration phase than it did during the validation period.

4.3. Results on the estimation of inflows into Raliphaswa weir

After calibrating and validating the SWAT model, inflows into the Raliphaswa weir, which supplies irrigation water to the three irrigation schemes, were extracted using ArcSWAT. The point in reach 15 was chosen to extract the inflow into the Raliphaswa weir.

Figure 4. 13 shows the simulated monthly inflows into the Raliphaswa weir using the SWAT model. The inflow simulation was done from September 1996 to December 2013. The highest peak recorded by the SWAT model was observed on the 1st of February 2000, which amounts to 79.44 million cubic metres per month. Data scarcity and uncertainty could have played a major role in the variation of the results. There were months where both models recorded low flows of zero million cubic metres.

The simulated peak flows were higher than the observed flows downstream of Mutshedzi Dam indicating that SWAT model (Figure 4. 14) did not underestimate them. There is a tributary which also contributes flows to Mutshedzi River downstream of the dam around Mauluma Village. This might have resulted in increased flows at the inflow point of Raliphaswa weir. This might be due to data gaps and limited of the data that is used in building and calibrating the SWAT model (the absence or availability or little observable data) (Mengistu *et al.*, 2019), generalised land use and soil data, unaccounted water abstractions, parameter generalisation, the uncertainty involved with daily flow simulations due to

variations in how the model forecasts flow and how observations are done to acquire observed flows (Obiero *et al.*, 2019) and the changes caused by the land-use activities and the underlying soils which accounted for during model setup.

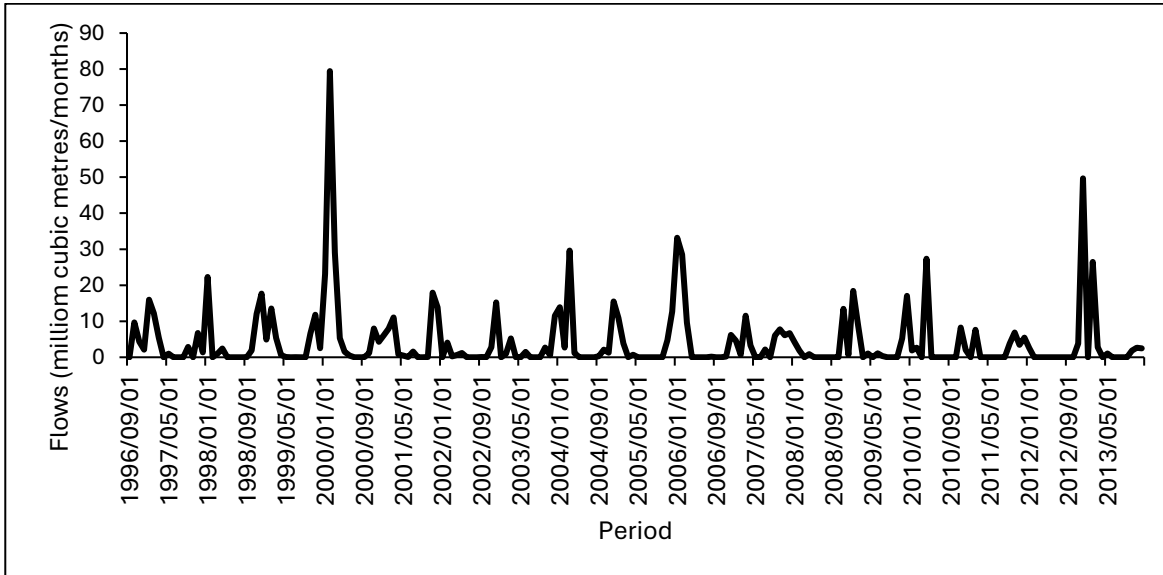


Figure 4. 13: Inflows into Raliphaswa weir.

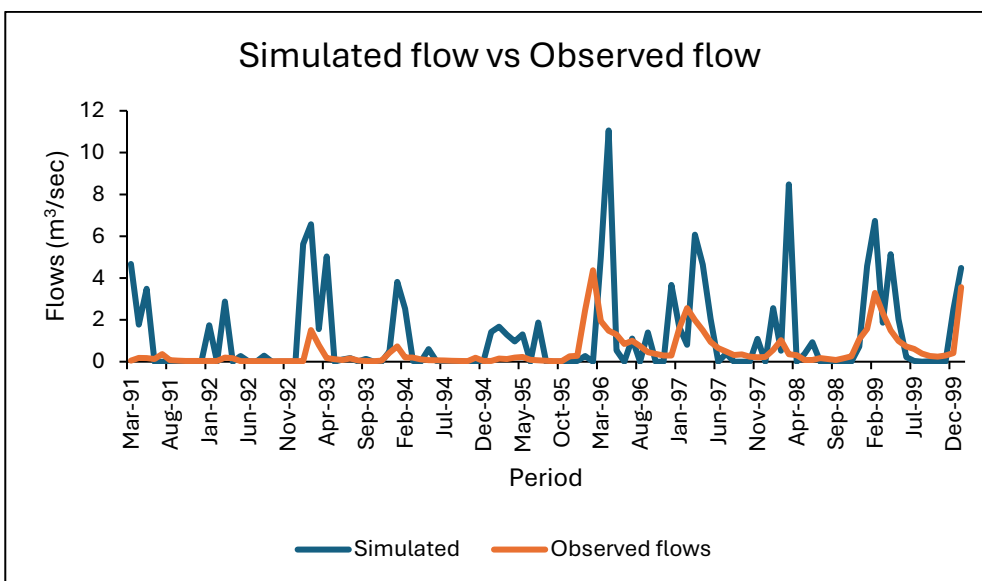


Figure 4. 14: Comparison of simulated flows and observed flows downstream of Mutshedzi.

Figure 4. 15 shows the expected water availability into the three irrigation schemes from SWAT model. The inflows into the irrigation schemes were determined using inflows from the Raliphaswa weir by adding incremental flows from the sub-catchment, accounting irrigation water demand. The study estimated crop water requirements using naturalized monthly flows using the Hargreaves approach. A detailed procedure on this can be found in a report by

Ndiritu *et al.* (2023). Most peak for the expected flows into the irrigation schemes were observed between December 2001 to December 2009.

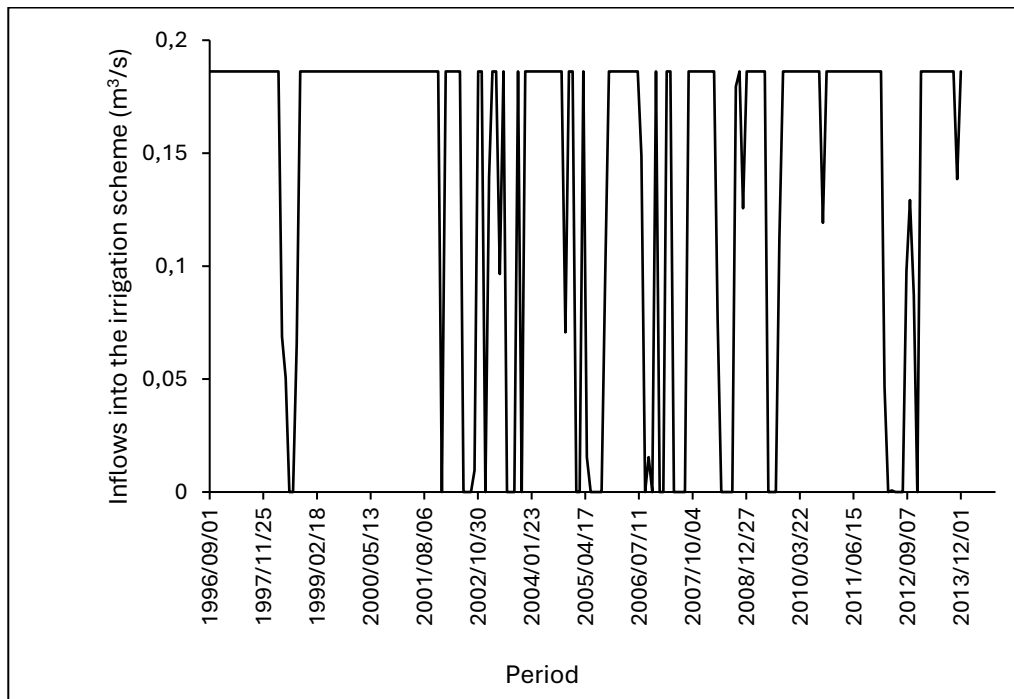


Figure 4. 15: Expected water availability.

Figure 4. 16 shows the flow duration curve from SWAT model that was used to determine the maximum flow capacity into the three irrigation schemes. The Raliphaswa weir was found to have a maximum flow capacity of 0.186 m^3/s . This flow rate was predicted 71.6% of the time and no flow was expected 17.8% of the time as seen using SWAT model.

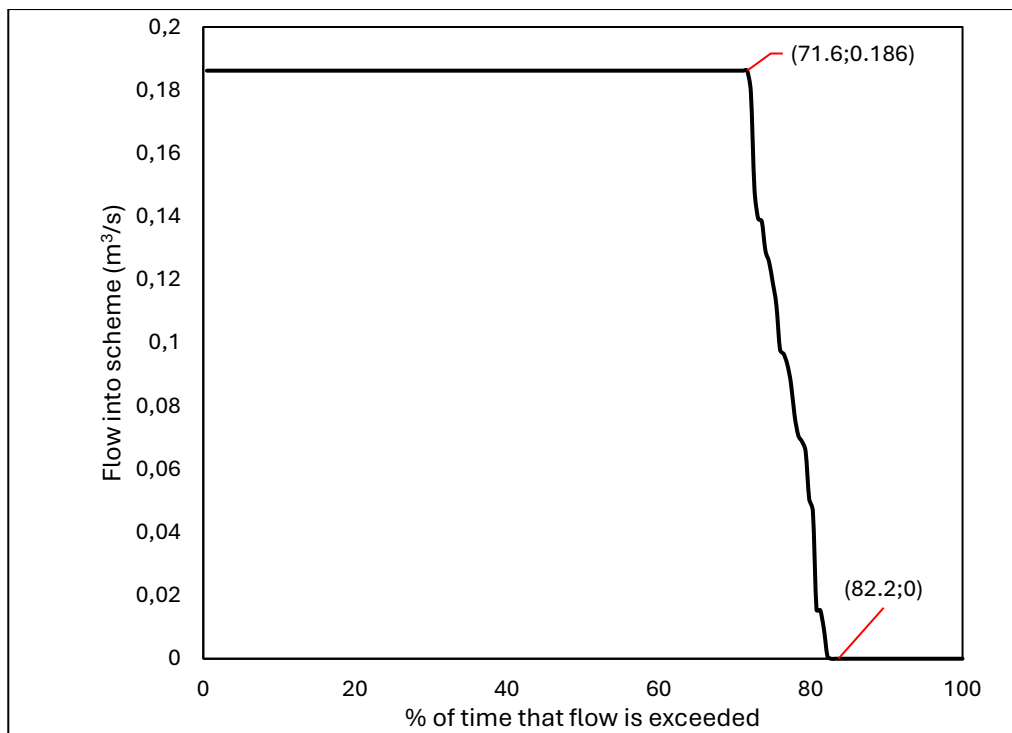


Figure 4. 16: Expected water availability flow duration curve.

4.4. Estimated crop water requirements results

4.4.1. Results on crop coefficient (K_c) curves and reference crop evapotranspiration (E_{To})

Daily E_{To} for the period of 35 years (1979 – 2014) was estimated using the Hargreaves equation. However, Figure 4. 17 presents results from the years 2005 to 2014 in order to get a clear view of the results. High daily E_{To} values were recorded, compared to the daily E_{To} values recorded by Abirdew (2018) because the study area experiences a hot, dry, windy, and sunny climate. The recorded daily E_{To} values ranged from 1.212 – 38.16 mm/day. The highest E_{To} was recorded on the 16th of February 1992 which was 38.16 mm/day, and it was recorded during the wet season when the area experiences high temperatures accompanied by dry winds.

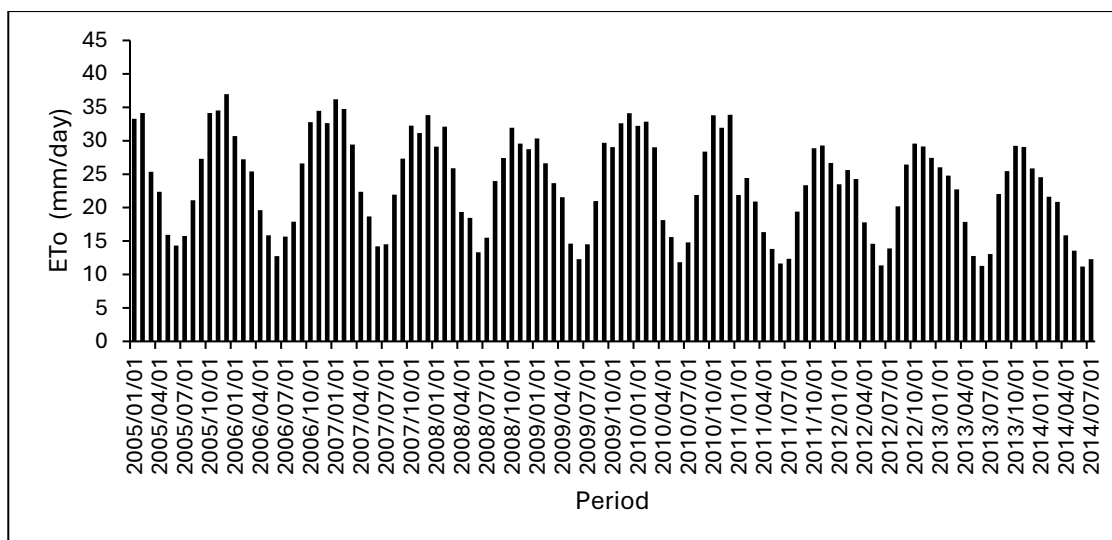


Figure 4. 17: Estimated daily ET_0 .

The K_c , which is known as the crop coefficient of a given crop is the ratio of the evapotranspiration of the crop (ET_c) to a reference crop (ET_0) (Piccinini *et al.*, 2007) and it is usually determined experimentally but, in this study, K_c of different crops were obtained from the CROPWAT model. According to Pokorny (2019), Opafola (2018) and Allen (1998) factors such as changes in leaf area, plant height, crop characteristics, irrigation method, rate of crop development, crop planting date, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices all have an impact on the K_c values. Different crops have different sets of crop coefficients that predict different water use at dissimilar stages of growth.

When a crop is small early in the sowing season, the water-use rate and K_c value are also low (K_c initial stage), and the crop ET rate increases as the plant grows. When agronomical plants are fully developed, the crop ET rate reaches its maximum (K_c mid-season) as presented in Table 4.6. The K_c is a very important parameter in crop evapotranspiration evaluation, this can be supported by the study done by Allen *et al.* (1998), De Medeiros *et al.* (2001), De Medeiros *et al.* (2005), Er-Raki *et al.* (2007), Williams and Ayars (2005). Table 4.6. shows K_c values and growing period for each crop. High K_c (1.23, 1.24, 1.15, 1.17, 1.05 and 1.15) values were recorded during the mid – stage in all crops. For those crops that are planted throughout the year, there was a slight difference in K_c values from the development stage to the late stage.

Table 4. 6: KC values and the growing period for each crop.

Crop	Initial stage	Dev stage	Mid stage	Late stage	Period (days)
Maize wet season	0.30	0.65	1.23	0.72	125
Maize (dry)	0.30	0.67	1.24	0.81	
Sweet potato (wet)	0.50	0.75	1.15	0.98	150
Sweet potato (dry)	0.50	0.76	1.17	1	
Green beans	0.50	0.71	1.05	1.03	90
Groundnuts	0.40	0.64	1.15	0.91	130

4.4.2. Results on crop water requirements

Figure 4. 18 shows computed daily crop water requirements of maize and total crop water requirements per growing season in both dry and wet season. Maize requires low quantity of water for irrigation in dry season and high quantity of water in wet season. The highest daily water requirement for maize in dry season was recorded on the 10th of August which was found to be 19.717 mm/day and 28.042 mm/day was recorded on the 5th of January during the wet season. The lowest daily crop water requirement during the dry season was recorded on the 10th of May and it was 1.742 mm/day and 2.485 mm/day in wet season, and it was recorded the 14th of November. The total crop water requirements in dry season ranged from 1047.9 – 1334.801 mm per growing season and 1520.87 – 2550.087 mm per growing season in wet season. There is a huge difference between the two growing seasons where dry season required much less water for irrigation. According to Brouwer and Heibloem (1986), maize crops with a growing period of 125 – 180 days requires a total of 500 – 800 mm/growing period. It is in the very same study where it was noted that factors such as climate, crop type, and crop growth stage have an influence in the required crop water for irrigation. High crop water requirements of maize were recorded as compared to the crop water requirements of maize reported in a study by Makungo and Nkuna (2022).

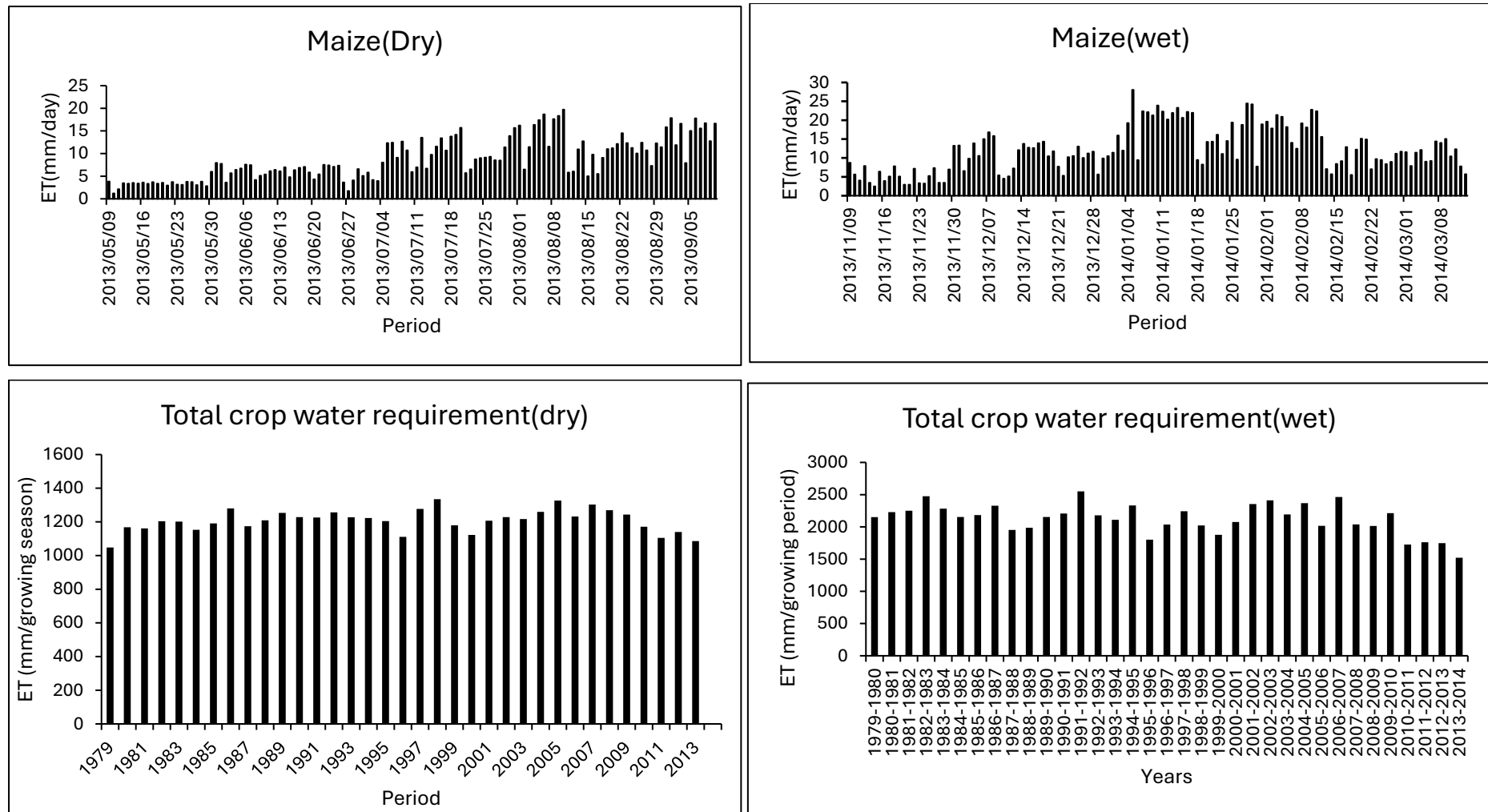


Figure 4. 18: Crop water requirements per day and total crop water requirements per growing season for maize for both dry and wet seasons.

Figure 4. 19 shows computed daily crop water requirements of sweet potato and total crop water requirements per growing season in both dry and wet season. The results showed that sweet potato requires small quantity of water for irrigation in dry season and large quantity of water in wet season. The lowest daily crop water requirement recorded in dry season was 6.118 mm/day which was recorded on the 7th of May and the highest crop water requirement in that season was 25.455 mm/day, recorded on the 18th of September. In wet season, the lowest crop water requirement of 3.61 mm/day, recorded on the 8th of October. The highest crop water requirement of 33.667 mm/day was recorded on the 23rd of November. The total crop water requirement of sweet potato in dry season ranged from 1648.40 – 1987.348 mm/growing season whereas the total crop water requirement in wet season ranged from 2265.502 – 3519.890 mm/growing season. The huge difference in crop water requirements during dry and wet season is influenced by the climate during that season. Even though the rainfall in wet season is sometimes relatively higher, the area also experiences high temperatures accompanied by dry, hot winds which increase evaporation and transpiration. The more water evaporates and transpires, the more crops need more water to maintain its optimum growth. In a study by Opafola *et al.* (2018) the early recorded and late irrigation water requirements for sweet potato were found to be 22.8 mm and 473.87 mm, respectively.

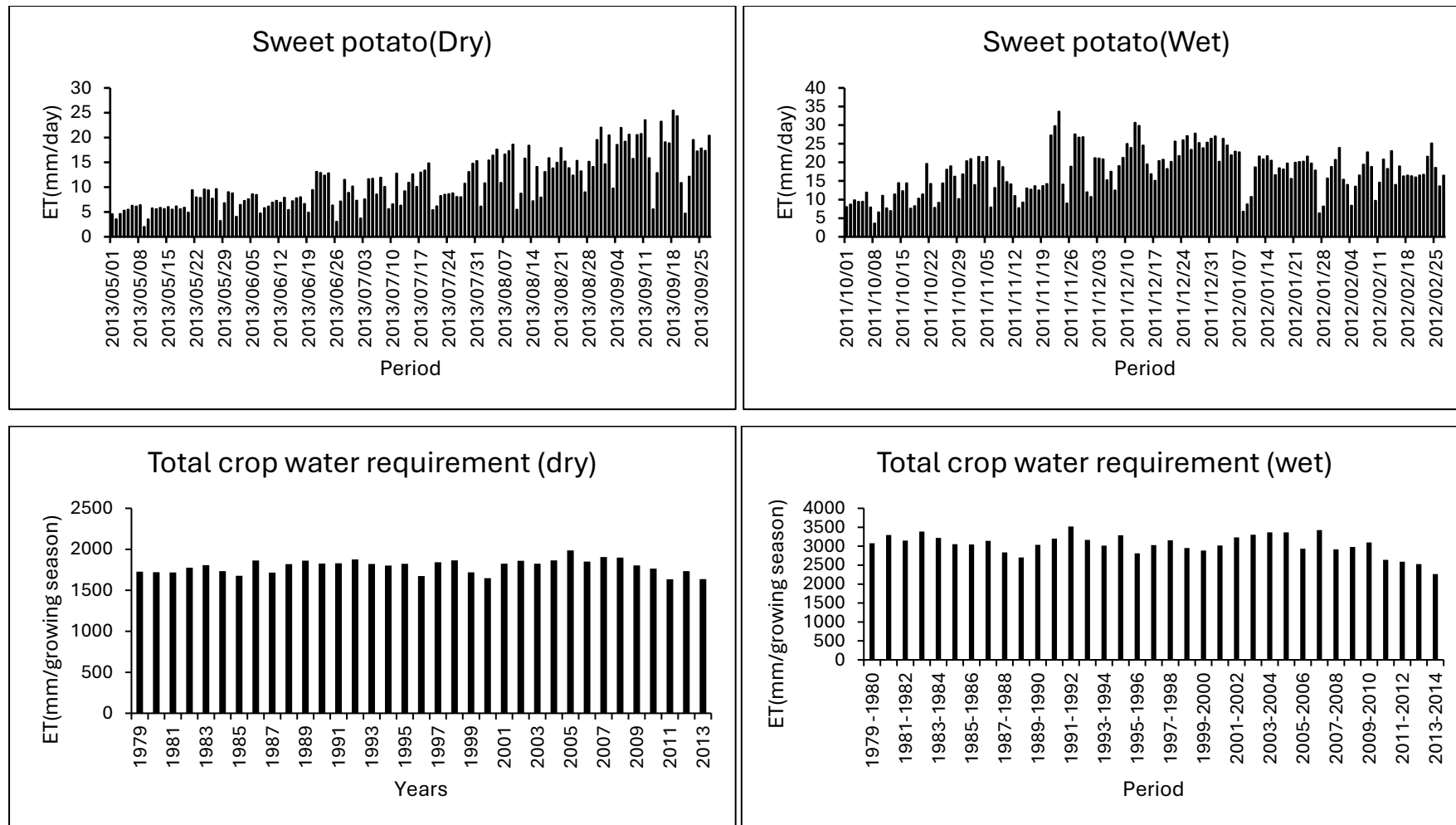


Figure 4. 19: Crop water requirements per day and total crop water requirements per growing season of sweet potato for both dry and wet seasons.

Figure 4. 20 shows computed daily crop water requirements of green beans in the study area. The lowest daily crop water requirement of 1.898 mm/day was recorded on the 9th of May together with the highest daily crop water requirement of 13.040 mm/day, recorded on the 20th of July. Figure 4. 21 shows the computed total crop water requirements per growing season. The total crop water requirements of green beans ranged from 612.549 – 844.429 mm per growing season. According to (ARC, n.d), green beans require around 450 mm of water, rainfall included during the growing season. A general rule of thumb is 35 mm/week which in this study is more than 35 mm per week with a daily crop water reaching a maximum of 13.040 mm. Green beans despise water on their seedlings as they germinate that is 5 - 7 days after sowing and they are highly susceptible to lack of moisture from the flowering stage onwards, therefore spray 35 mm per week until the pods are harvested. The high crop water requirements observed in the current study could be because of the varying climate and soil characteristics of the study area. In a training manual by Brouwer and Heibloem (1986) it was noted that green beans with a growing period of 75–90 days requires total irrigation water of about 300 – 500 mm/growing season. The computed crop water requirements of green beans in the current study are higher than the recommended range of 450 mm by ARC (n.d) and 300 – 500 mm by Brouwer and Heibloem (1986). Borosic *et al.* (2000) found that green bean crop evapotranspiration (ET_c) amounted to 400 mm per growing in Zagreb. The variability in ET_c values could be attributed to different irrigation schedules used and the diverse climate conditions. Sezen *et al.* (2008) observed that green bean ET_c values varied between 253 mm and 338 mm, noting that seasonal crop evapotranspiration values rose as both the irrigation schedule and interval decreased.

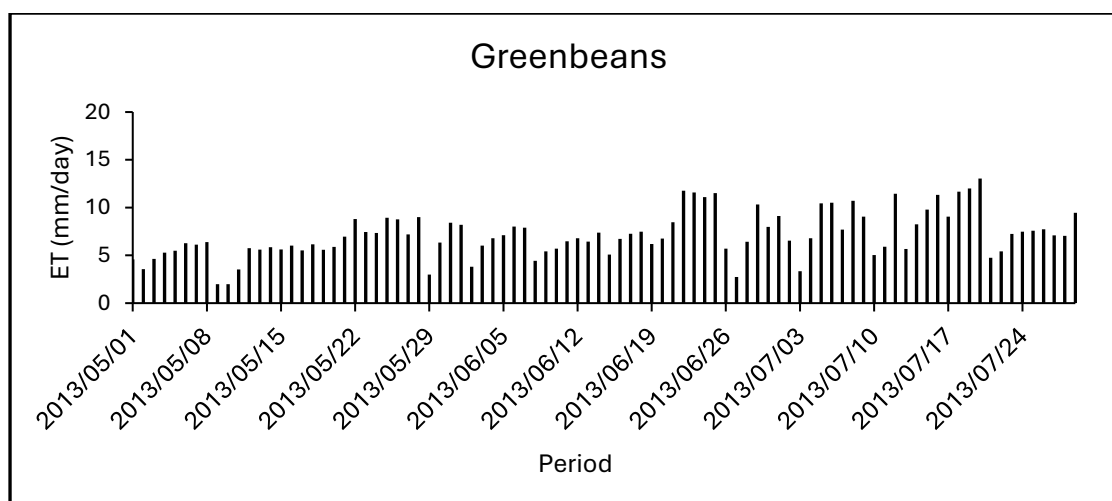


Figure 4. 20: Daily crop water requirements of green beans.

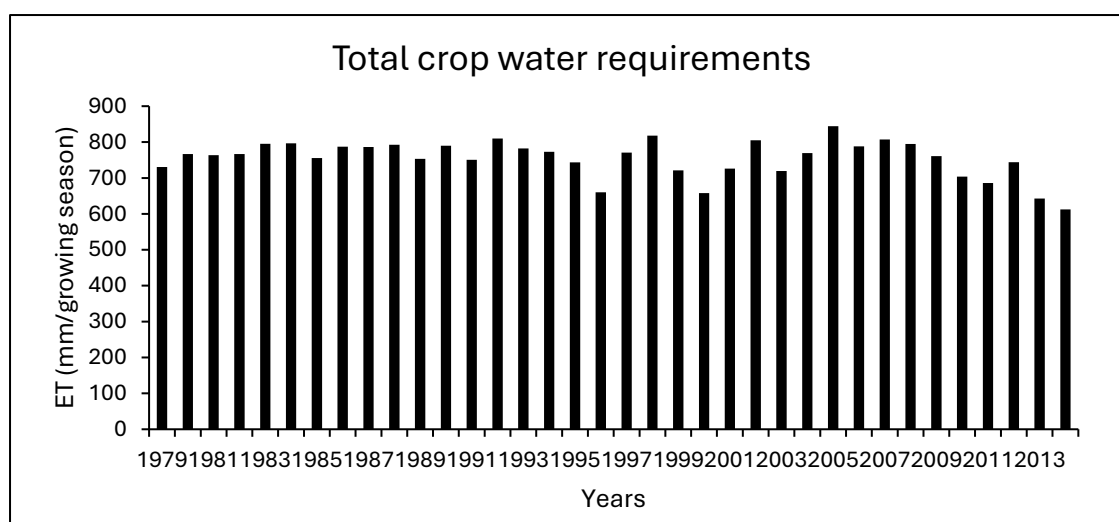


Figure 4. 21: Total crop water requirements of green beans per growing season.

Figure 4. 22 shows the daily crop water requirements of ground nuts. The lowest daily crop water requirement was recorded on November 22nd and it was about 2.773 mm/day and highest crop water requirement was recorded on the 26th of January, amounting to 29.921 mm/day. Figure 4. 23 shows the total crop water requirements of groundnuts per growing season. The total crop water requirements for the entire growing season ranged from 1658.110 – 2723.812 mm per growing season. According to Brouwer and Heibloem (1986) groundnuts with a growing period of 130 – 140 days requires a total required irrigation water of about 500 – 800 mm per growing season. The recorded crop water requirements of the current study are much higher than that recommended by Brouwer and Heibloem (1986). Singh also noted low daily crop water

requirements *et al.* (2013), the study was done in an area where drip irrigation was applied.

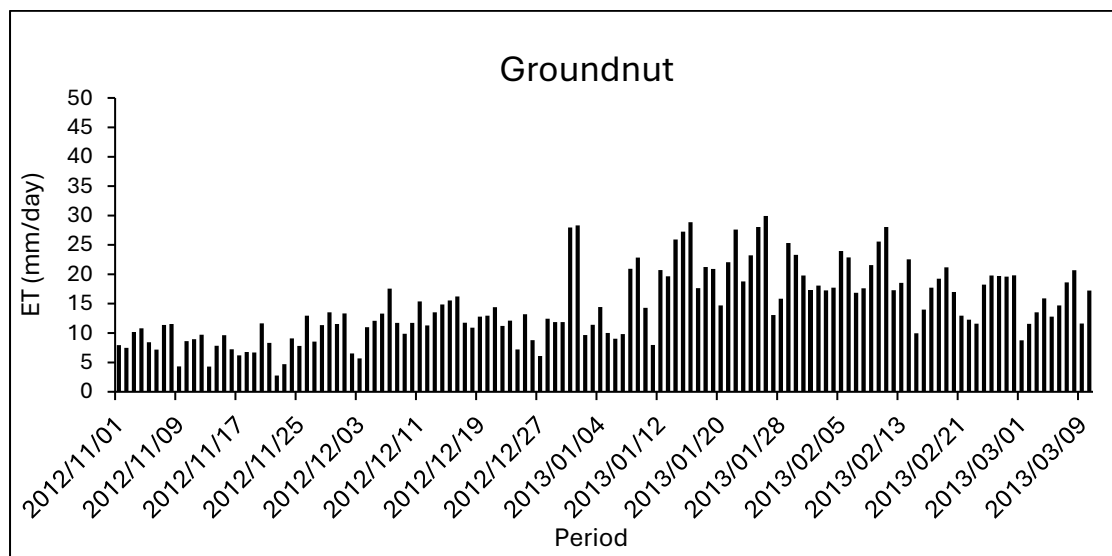


Figure 4. 22: Daily crop water requirements of groundnuts.

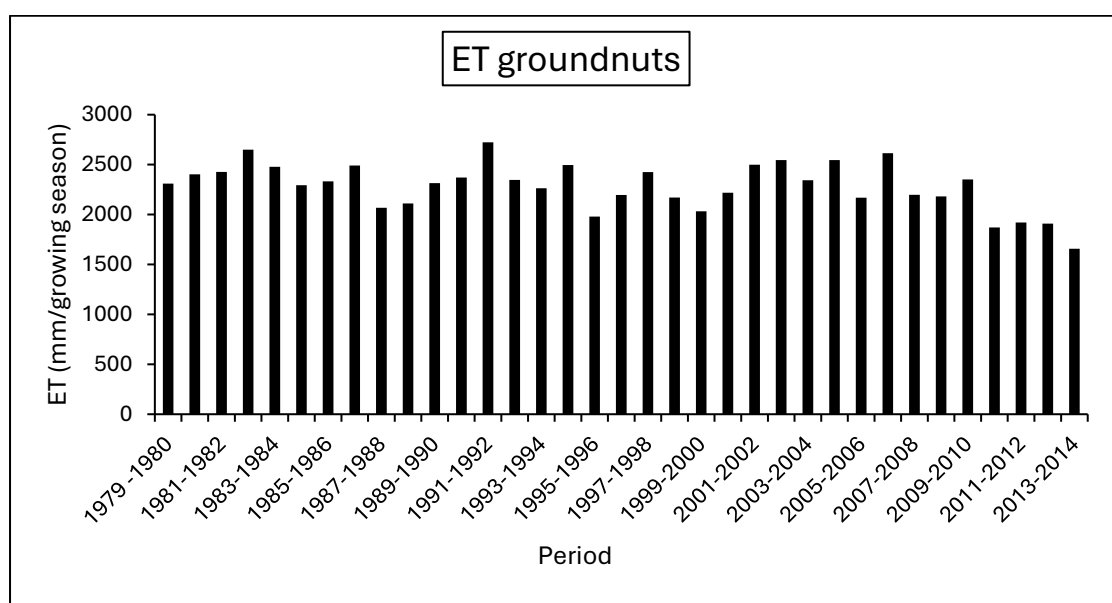


Figure 4. 23: Total crop water requirements of groundnuts per growing season.

4.5. Results on comparison of water conveyed to the irrigation schemes and the crop water requirements

Figure 4. 24 to Figure 4. 29 show the relationship between monthly water conveyed to the irrigation schemes considering 60% conveyance and the computed monthly crop water requirements of maize in wet season. The results showed that there is enough water to meet the crop water requirements of maize during wet season. It is in this

season where the weir overflows due to the rainfall received. The highest monthly inflow was recorded in January 2009 where it reached 11260529 m³/month. The year 2009 was a wet year and the peak of the inflows might have been influenced by the amount of rainfall received, supported by a study done by Mazibuko *et al.* (2021). The highest crop water requirement was recorded in January 2003 which was approximately 169379.60 m³/month.

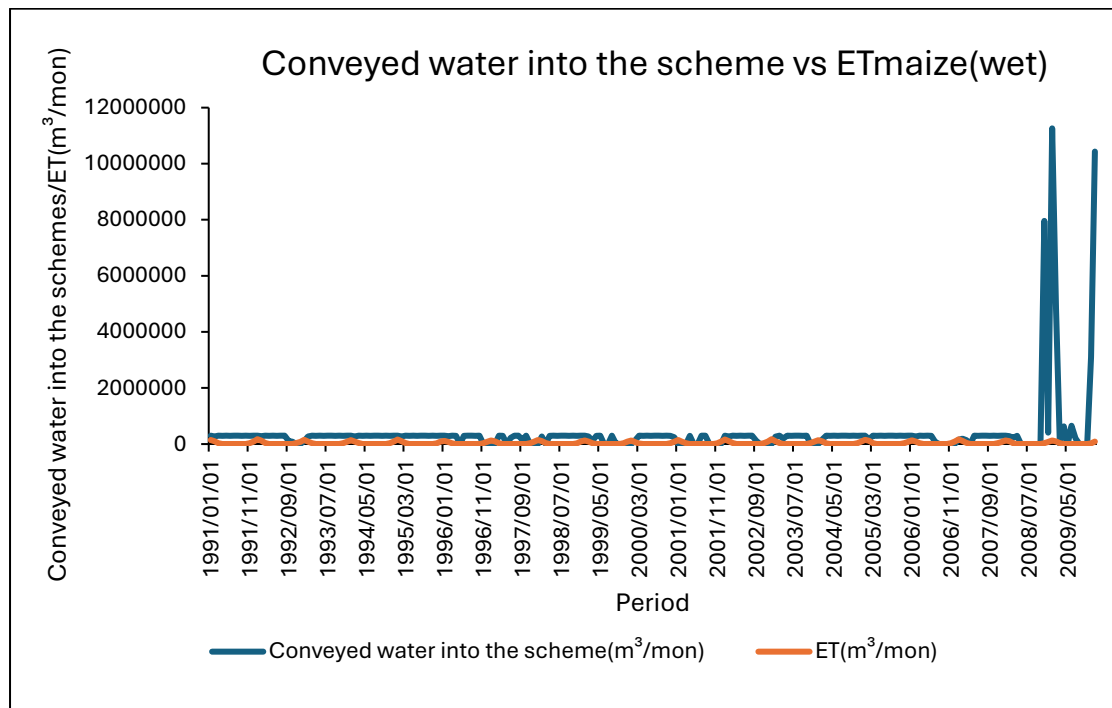


Figure 4. 24: Relationship between monthly conveyed water and crop water requirements of maize in wet season.

Figure 4. 25 showed that the available water can meet the crop water requirements of maize for the entire dry season. Even though the area receives low rainfall in the dry season leading to reduced water levels in the Raliphaswa weir, the available water is also able to meet the crop water requirements of maize. The highest crop water requirement was recorded in August 2001 which was approximately 2585.28 m³/month.

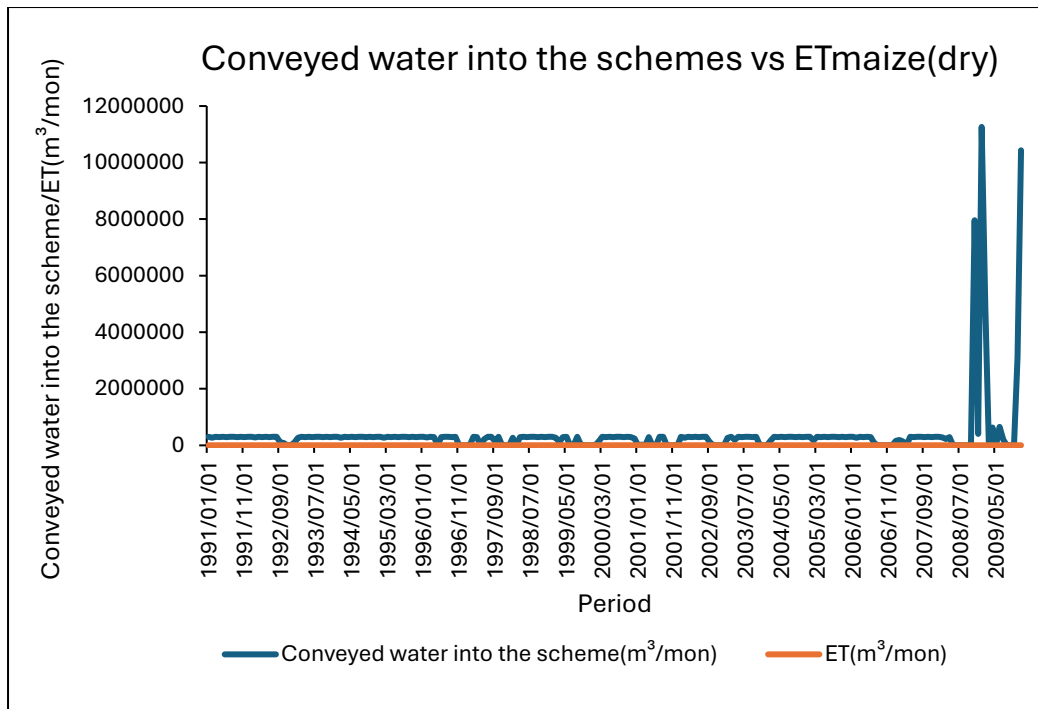


Figure 4. 25: Relationship between monthly conveyed water into the schemes and crop water requirements of maize in dry season.

Figure 4. 26 showed that there is enough available water to meet the crop water requirements of sweet potato in dry season. Sweet potatoes are an extremely minimal maintenance crop that even when neglected, continues to yield well. Although they can withstand dry periods and low water, they yield more when well-watered (Sustainable Holly, 2021 and Motsa *et al.*, 2015). The highest crop water requirement was recorded in August 2001 which was approximately 2585.28 m³/month.

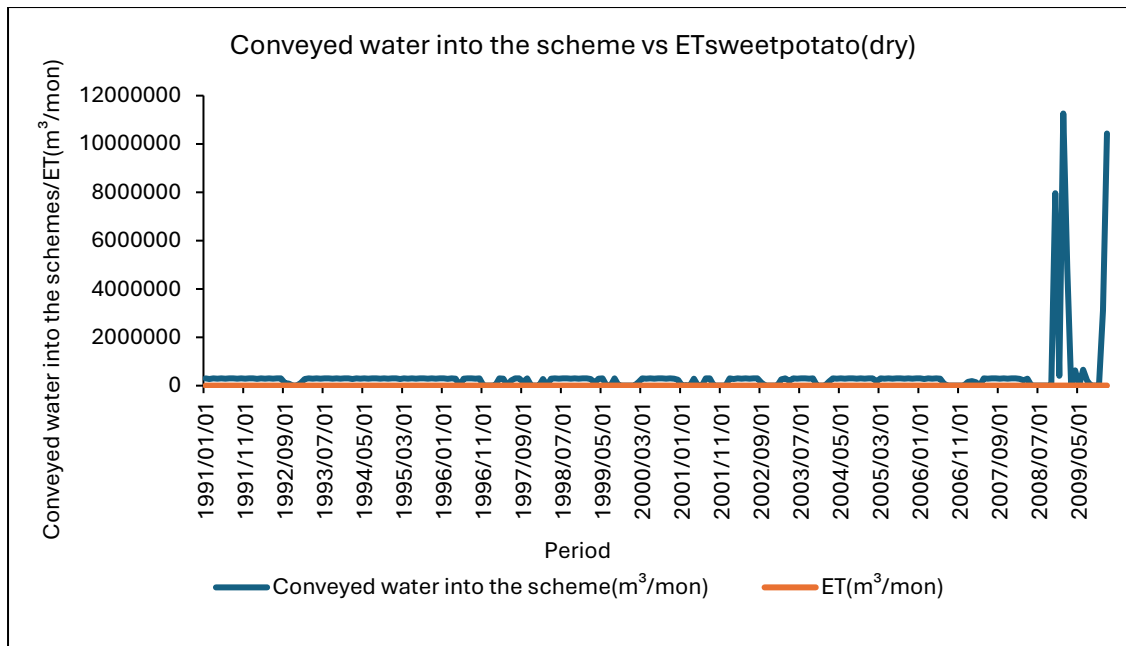


Figure 4. 26: Relationship between monthly conveyed water into the scheme and crop water requirements of sweet potato in dry season.

Figure 4. 27 showed that the available water is more than enough to meet the crop water requirements of sweet potato during wet season. The crop water requirements of sweet potato in wet season are much higher compared to the water requirements in dry season, the available irrigation water is enough to meet the water required by sweet potato. The availability of irrigation water together with high temperatures during summer favours production of high-quality sweet potatoes (Felix *et al.*, 2015) The highest crop water requirement was recorded in December 2003 which was approximately 5030.018 m³/month.

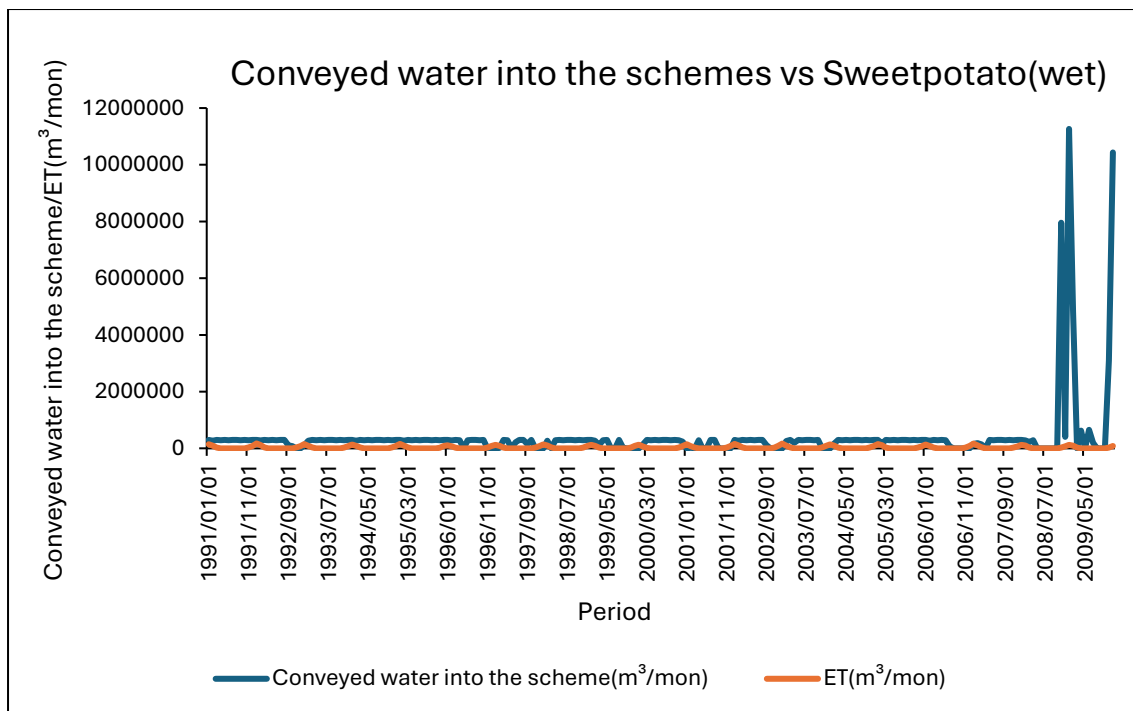


Figure 4. 27: Relationship between monthly conveyed water into the schemes and crop water requirements of sweet potato in wet season.

Figure 4. 28 showed that the available water is insufficient to meet the crop water requirements of green beans for the entire growing season. The highest crop water requirement was recorded in July 2005 which amounts to 2099823.606 m^3/mon .

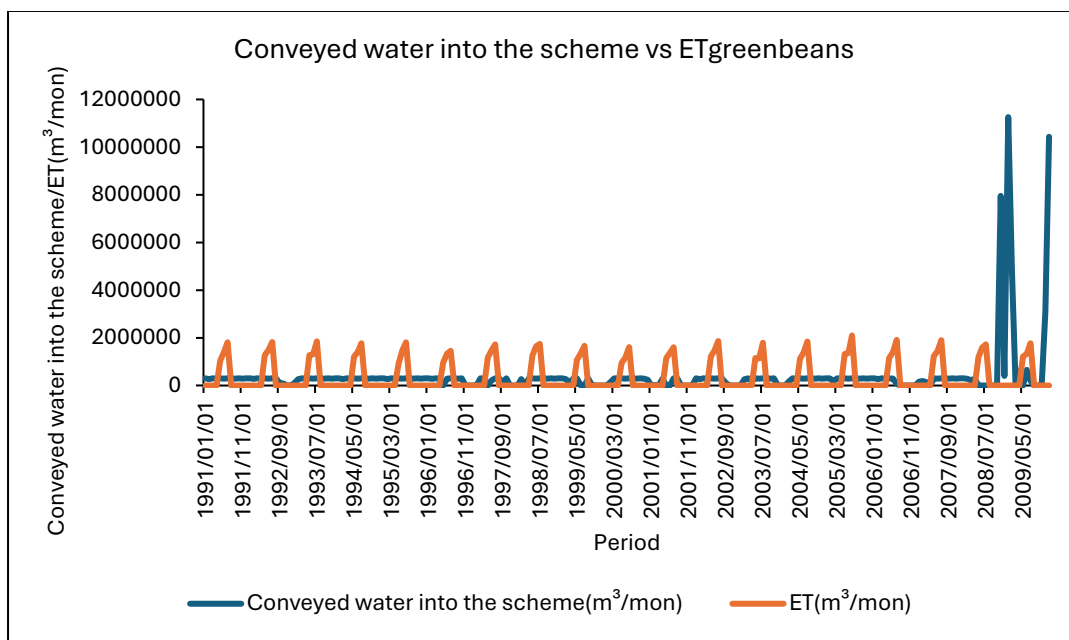


Figure 4. 28: Relationship between monthly conveyed water into the scheme and crop water requirements of green beans.

Figure 4. 29 the conveyed water into the schemes is lower than what the groundnut requires. The highest monthly crop water requirement of groundnut was recorded in

January 2007 and it was about 1048540.501 m³/mon. The available water was able to meet the crop water requirements of groundnuts from November 2008 to December 2009.

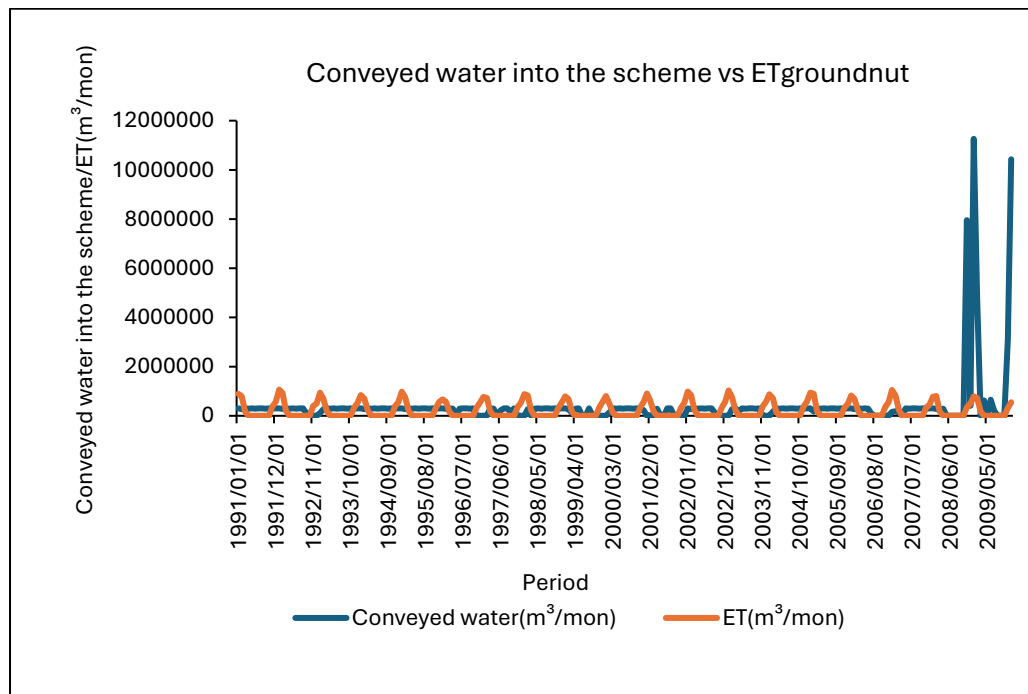


Figure 4. 29: Relationship between monthly conveyed water into the schemes and crop water requirements of groundnut.

4.6. Uncertainty Propagation in ETo Estimation and Conveyance Efficiency Assumptions

Uncertainty is essential in hydrological modelling, particularly in data-scarce environments where some parameters must be estimated or assumed. In this study, two key areas where assumptions may influence results reliability are reference evapotranspiration (ETo) estimation and irrigation conveyance efficiency.

The Hargreaves equation was used to estimate ETo due to the unavailability of complete climate data (solar radiation, wind speed, and relative humidity) required for the FAO Penman-Monteith method. While the Hargreaves method is widely accepted for use in semi-arid and data-limited regions (Odhiambo et al., 2021), it is known to produce variable results under humid or extremely dry conditions (Tabari et al., 2013).

This introduces potential uncertainty into the crop water requirement (CWR) calculations, which are sensitive to ETo values. Therefore, while appropriate for this

study context, the use of Hargreaves may have caused over- or underestimation of actual crop demand.

In addition, the study also applied a conveyance efficiency value of 60%, based on values reported in the literature for smallholder schemes in South Africa (Backeberg, 2003; Bastiaanssen et al., 2001). This fixed value does not reflect variations between schemes due to canal conditions, leakage, and management practices. As a result, the actual volume of water delivered to fields may differ from the estimates used in this study.

These assumptions were necessary to allow model simulation in the absence of measured field data. However, they represent potential sources of uncertainty in both water availability and irrigation demand estimates. The results should therefore be interpreted with this context in mind, and future research is encouraged to:

- Conduct field-based verification of conveyance losses;
- Collect full climate datasets for improved ETo estimation; and
- Perform sensitivity analysis to quantify the impact of these assumptions on model outcomes.

4.7. Recommendation of types of crops that can be planted at the schemes

The area requires plants that are resistant to drought (high temperatures) and requires little water for irrigation. The following crops are recommended considering not just climate, but also market potential, water demand, crop duration, soil compatibility, local preference, and economic viability.

Cowpeas: Cowpeas are a short-duration legume crop with relatively low water demand, making them ideal for intermittent irrigation. Beyond their climate tolerance, they are nutrient-dense, used in multiple dishes, and widely consumed locally, increasing their household food security value. Additionally, their ability to fix atmospheric nitrogen helps improve soil fertility for rotational cropping systems (Singh et al., 2017).

Butternut Squash: Butternut is increasingly popular in South African markets and has high market demand, both in fresh produce and processing industries. It is a high-yielding crop with moderate water requirements and grows well on loamy soils found

in parts of Nzhelele. Its relatively long shelf life makes it suitable for smallholder farmers with limited cold storage infrastructure (Shayanowako et al., 2021).

Sunflowers: Sunflowers are not only moderately water-efficient, but they also have strong economic potential due to demand from the edible oil industry. They tolerate a wide range of soil types and offer the benefit of residual income through seed sales. Additionally, the crop fits well within conservation agriculture systems practiced by some smallholders (Botha et al., 2015).

Sorghum: Sorghum is a staple grain with growing demand for both human consumption and animal feed. It has low water requirements, is resistant to common pests, and suits the socio-economic conditions of smallholders. Moreover, it provides fodder residue, supporting mixed farming systems (du Plessis, 2008).

Onions (*Allium cepa*): Onions have high market value, and their production can be staggered for better pricing. Although they require consistent moisture during bulb development, their economic return per unit of water used is favourable when irrigation is properly scheduled. They are also well suited for manual labour, which aligns with the labour capacity in smallholder settings (FAO, 2012).

Cabbage: Cabbage is popular in local diets and is in constant demand across formal and informal markets. It has moderate water requirements, grows well during cooler months (reducing water loss), and offers relatively quick returns with proper irrigation. It also aligns well with mixed cropping systems (DAFF, 2010).

CHAPTER FIVE: CONCLUSIONS, RECOMMENDATIONS AND LIMITATIONS

5.1. Conclusions

The study was aimed at modelling hydrology for estimating water availability for irrigation supply in selected schemes in the Nzhelele area. Using a calibrated and validated SWAT model, daily inflows into Raliphaswa, Mandiwana and Mamuhohi irrigation schemes were computed. The SWAT model results showed a good model performance, this was noted from the performance indicators that were used in this study which include R^2 , NSE and PBIAS which showed positive results for both calibration and validation periods though failed to simulate baseflow due to the uncertainties in the data used. The inflows into the scheme were found to be sufficient to meet crop water requirements of maize and sweet potato in both dry and wet growing seasons and insufficient to meet the crop water requirements of green beans and groundnuts. The crop water requirements were not met for the entire growing season while the crop water requirements of groundnuts were only met from November 2008 to December 2009. Though the Hargreaves formula overestimates ET, it was found to be a good ET estimator in the current study due to its data requirements, and it was used with the Kc values to determine the crop water requirements of major crops (maize, sweet potatoes, groundnuts, and green beans) planted in the area. The crop water requirements for all crops were found to increase with a development stage, which is the water-use rate values were small in the initial stage and high during the fully development stage. Therefore, it can be concluded that crop water requirement increases as the plant grows, and high daily crop water was observed for all the major crops planted in the three irrigation schemes.

5.2. Recommendations

Based on the findings of this study, the following recommendations are proposed to improve the functionality, water use efficiency, and sustainability of smallholder irrigation schemes in the Nzhelele area:

Improve monitoring of water inflows and usage: The absence of flow monitoring in the schemes hampers effective irrigation planning. It is recommended that simple and cost-effective flow measurement infrastructure (e.g., staff gauges, data loggers) be installed to enable real-time tracking of inflows and scheme-level water use.

Adopt water-saving irrigation techniques: Given the limited water availability and conveyance efficiency, smallholder farmers should be encouraged to adopt more efficient irrigation methods, such as drip or furrow irrigation, where feasible. These methods help reduce water loss and improve application efficiency compared to traditional flood irrigation.

Align crop selection with available water: The study revealed that some crops, such as maize and sweet potato, can be sustained under current water supply conditions, while others like groundnuts and green beans exceed available water. Future cropping decisions should be based on seasonal water availability and the crop's specific water demand to avoid water stress and yield loss.

Develop scheme-level irrigation scheduling plans: Irrigation scheduling should be informed by actual crop water requirements and local inflow patterns. Developing simple, tailored irrigation calendars using tools such as CROPWAT or derived from SWAT outputs can help farmers apply the right amount of water at the right time.

Rehabilitate and maintain conveyance infrastructure: Water losses along canals and pipes due to leakages and poor maintenance reduce the actual water delivered to fields. Infrastructure rehabilitation should be prioritised to improve conveyance efficiency, estimated at 60% in this study, and ensure equitable water distribution among farmers.

Strengthen institutional support and farmer training: Extension services should be enhanced to provide training on irrigation scheduling, crop selection under water constraints, and system maintenance. Empowering Water User Associations to participate in scheme management and water allocation decisions will improve long-term scheme sustainability.

Incorporate localised data into scheme planning: Future planning for scheme rehabilitation and expansion should be based on localised hydrological modelling and updated land use data. Tools like SWAT can support this by simulating catchment inflows under different land and water management scenarios.

Implementing data-filling techniques could potentially enhance the reliability of model simulations by reducing input data uncertainty. For instance, more accurate rainfall inputs would likely improve SWAT model performance during both calibration and

validation. Similarly, better quality evapotranspiration data would refine crop water requirement estimations, leading to more informed irrigation planning.

Therefore, while this study focused on the broader objectives of estimating water availability and crop suitability, future work could benefit significantly from addressing data gaps through robust data-filling methodologies.

5.3. Limitations of the Study

While this study provides valuable insights into the estimation of water availability and crop water requirements in smallholder irrigation schemes, it is important to acknowledge certain limitations that may have influenced the accuracy and applicability of the results:

Limited Availability of Observed Hydrological and Climate Data: The reliability of SWAT model outputs depends heavily on the quality and continuity of input data. In this study, there were notable gaps in observed rainfall, temperature, and streamflow records due to damaged or poorly maintained monitoring infrastructure. As a result, the SWAT weather generator was used to fill missing climate data, which, although useful, may not fully replicate local variability.

Use of Hargreaves Equation for ETo Estimation: The reference evapotranspiration (ETo) was estimated using the Hargreaves method, which relies only on minimum and maximum temperature data. While this method is suitable for data-scarce environments, it is less accurate than the FAO Penman-Monteith method, which incorporates wind speed, solar radiation, and humidity. This simplification may have introduced uncertainty into the calculated crop water requirements.

Fixed Crop Parameters and Uniform Irrigation Efficiency Assumption: The study used generalized crop coefficients (K_c values) and assumed a uniform conveyance efficiency of 60% across all schemes. These assumptions may not reflect the actual conditions in each scheme, as local irrigation methods, infrastructure conditions, and management practices vary. This affects the precision of irrigation requirement estimates and the suitability of recommended crops.

Model Calibration Constraints: The SWAT model was calibrated and validated using limited observed streamflow data, particularly for the small-scale catchments feeding the selected schemes. The moderate model performance (e.g., $NSE = 0.56$) indicates

reasonable but not high predictive power, which could be improved with more detailed calibration datasets.

Exclusion of Socio-Economic and Institutional Factors: While the study focused on hydrological and technical aspects of water availability, it did not integrate socio-economic factors such as farmer decision-making, market access, or institutional support, which are also critical for the sustainability of irrigation schemes.

Short-Term Assessment: The study is based on historical climate and hydrological data (1987–2014) and does not account for future climate change impacts, which may further influence water availability and irrigation needs in the long term.

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APPENDICES

Appendix A: Questionnaires

A. Farmers Details

A1. On which scheme is your plot located?

- ☐ Raliphaswa
- ☐ Mamuhohi
- ☐ Mandiwana

A2. What are the coordinates of the plot centroid? (decimal deg) - to be completed by interviewer

- Latitude: _____
- Longitude: _____

A3. When did you join the scheme?

- Year: _____
- Month: _____

A4. Why did you join the scheme?

A5. What is your gender?

- ☐ Male
- ☐ Female

A6. What is your highest level of education?

- ☐ No formal education
- ☐ Primary School
- ☐ High School
- ☐ Tertiary

A7. Is the farm-land registered under your name? If yes, skip to A11

- ☐ Yes
- ☐ No

A8. If the land is not registered under your name, then who is it registered under?

A9. Do you farm on a full-time basis? If yes, skip to A11

- ☐ Yes
- ☐ No

A10. If not, what is your main occupation? _____

B. LAND AND CROPS GROWN

B1. What is the total annual income from farming per annum?

- Rands: _____

B2. What is the total annual expenditure on agricultural production per annum?

- Rands: _____

B3. Do you consider the size of the plot:

- ☐ Too small
- ☐ Just right
- ☐ Too large

B4. What form of land control of your plot do you have?

- ☐ Ownership
- ☐ Leasehold
- ☐ Permission to occupy (PTO)
- ☐ Building permit
- ☐ Trading permit
- ☐ Other (specify): _____

B5. How much do you pay towards this form of land control?

- ☐ Nothing
- ☐ <10% of annual income
- ☐ >10% and <30%
- ☐ >30% and <50%

- ☐ >50% and <70%
- ☐ >70% of income

B6. Are you aware of the rights you have to the land?

- ☐ Yes
- ☐ No

B7. If yes, are you permitted to sell or rent out a piece of your plot?

- ☐ Yes
- ☐ No
- ☐ I don't know

B8. Does the tenure security of the land influence your land use decision?

- ☐ Yes
- ☐ No
- If yes, how so? _____

C. FARMER WATER ACCESS AND USE

C1. How do you decide when to irrigate? (Select all that apply)

- ☐ By feeling and seeing how wet or dry the soil is
- ☐ Rainfall in the past few days
- ☐ I check the state of the crops
- ☐ Rule of thumb
- ☐ Experience
- ☐ Memory
- ☐ Information from neighbours
- ☐ Information from management
- ☐ Information from extension service providers
- ☐ Soil Water Balance Model (SWB)
- ☐ Irrigation calendars
- ☐ BEWAB (Irrigation Water Management Program)

- ☐ Maximum crop evapotranspiration
- ☐ Other (specify): _____

C2. Do you experience water restrictions / shortages of supply expected in the summer?

- ☐ Yes
- ☐ No

C3. Do you experience water restrictions / shortages of supply expected in the winter?

- ☐ Yes
- ☐ No

C4. If yes, what do you do to manage the shortage?

- ☐ Reduce the area irrigated
- ☐ Store water for use during shortages
- ☐ Reduce sow area based on reduced water supply
- ☐ Minimise irrigation per crop
- ☐ Other (specify): _____

C5. Do you receive water at the required flow rate in winter?

- ☐ Yes
- ☐ No

If not, why? _____

C6. Do you receive water at the required flow rate in summer?

- ☐ Yes
- ☐ No

If not, why? _____

C7. Do you have access to agriculture extension services?

- ☐ Yes
- ☐ No

If yes, how many visits in a month or in a year? _____

Appendix B: Informed Consent

RESEARCH ETHICS COMMITTEE

UNIVEN Informed Consent

Appendix B

LETTER OF INFORMATION

Title of the Research Study: Hydrological modelling for estimating water availability for irrigation supply in selected schemes in Nzhelele area, Limpopo Province.

Principal Investigator/s/ researcher : *(Mbaimbai V., Honours (Hydrology))*

Co-Investigator/s/supervisor/s : *(Dr Makungo R., PhD (Hydrology))*
(Prof Ndiritu J.G., PhD (Engineering))

Brief Introduction and Purpose of the Study: the study focuses on hydrological modelling for estimating water availability for irrigation supply in selected scheme in Nzhelele area. to identify an efficient model for estimating water availability for irrigation supply and determine the extent to which available water can meet the irrigation water requirements using hydrological model. In South Africa, one of the most significant observations regarding smallholder irrigation farming is that small farmers seem to apply much less irrigation water than is recommended for conventional full irrigation (DWA, 2007, Frenken, 2005). Therefore, there is a need to investigate actual crop water use to enable recommendations for matching water availability to demand such as lower planting densities and low-input cultivation methods. Irrigation plays a major role in feeding the expanding populations and it will continue to play a bigger role in the future (Balarane, 2015). Thus, determining the amount of water required for irrigation will increase the chance of water use sustainability while improving performance of smallholder irrigation schemes.

Outline of the Procedures : *(Responsibilities of the participant, consultation/interview/survey details, venue details, inclusion/exclusion criteria, explanation of tools and measurement outcomes, any follow-ups, any placebo or no treatment, how much time required of participant, what is expected of participants, randomization/ group allocation)*

The participants will be provided with a copy of the questionnaire in advance to assist them to prepare for the interviews. Participant will confidentially be screened before the interviews to determine those who have symptoms and/or are vulnerable (i.e. those who are over the age of 50 and/or have underlying health conditions) to COVID-19. Arrangements will be made for the interviews with the low risk participants to be done in person while interviews with the medium to high risk participants will be done

remotely via phone or Whatsapp. The interviews with the farmers will take 1.5 – 2 hours each, the interviews with the scheme committee members will take 45 – 60 minutes and the meetings with the scheme operations team members will take 20 – 30 minutes.

Risks or Discomforts to the Participant: *(Description of foreseeable risks or discomforts to for participants if applicable e.g. Transient muscle pain, VBAI, post-needle soreness, other adverse reactions, etc.)*

The risk of infection/transmission of COVID-19 will be minimised by screening participants and sanitising hands and manmade surfaces including the chairs and tables, before and after the interviews.

Benefits : *(To the participant and to the researcher/s e.g. Publications)*

The participants will have access to information on estimated crop water use in the farms, ways to improve their farming practices and market access after completion of the study.

Reason/s why the Participant May Be Withdrawn from the Study: *(Non-compliance, illness, adverse reactions, etc. Need to state that there will be no adverse consequences for the participant should they choose to withdraw)*

Participants who show symptoms of COVID-19 and/or are within vulnerable groups will be withdrawn from the study. There will be no adverse consequences for the participant should they choose to withdraw

Remuneration : None

Costs of the Study : None

Confidentiality : Information collected during the meetings will be kept in confidence by the project team members and will not be shared without the consent of the participants. Furthermore, the interviews will be conducted individually and not in groups. Care will also be taken to ensure that the research findings are not presented in a way that would enable the identification of or prejudice a participant.

Research-related Injury : No research related injuries are expected to happen.

Persons to Contact in the Event of Any Problems or Queries:

Ms V. Mbaimbai (contact number: 0722704778) or the University Research Ethics Committee Secretariat on 015 962 9058. Complaints can be reported to the Director: Research and Innovation, Prof G.E. Ekosse on 015 962 8313 or Georges Ivo.Ekosse@univen.ac.za

General:

Potential participants must be assured that participation is voluntary and the approximate number of participants to be included should be disclosed. A copy of the information letter should be issued to participants. The information letter and consent

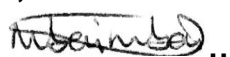
form must be translated and provided in the primary spoken language of the research population

CONSENT

Statement of Agreement to Participate in the Research Study:

- I hereby confirm that I have been informed by the researcher, (*Mbaimbai Vhahangwele*), about the nature, conduct, benefits and risks of this study - Research Ethics Clearance Number: _____,
- I have also received, read and understood the above written information (*Participant Letter of Information*) regarding the study.
- I am aware that the results of the study, including personal details regarding my sex, age, date of birth, initials and diagnosis will be anonymously processed into a study report.
- In view of the requirements of research, I agree that the data collected during this study can be processed in a computerized system by the researcher.
- I may, at any stage, without prejudice, withdraw my consent and participation in the study.
- I have had sufficient opportunity to ask questions and (of my own free will) declare myself prepared to participate in the study.
- I understand that significant new findings developed during the course of this research which may relate to my participation will be made available to me.

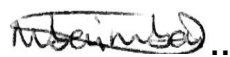
Full Name of Participant	Date	Time	Signature
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I, Mbaimbai Vhahangwele	...09/09/2020...	...17H00.....	...
			

(*Name of researcher*) herewith confirm that the above participant has been fully

Informed about the nature, conduct and risks of the above study.

Full Name of Researcher

... Mbaimbai Vhahangwele ...	Date...09/09/2020...	Signature...
		

Full Name of Witness (If applicable)

...N/A..... Date Signature.....

Full Name of Legal Guardian (If applicable)

...N/A..... Date..... Signature.....

Please note the following:

Research details must be provided in a clear, simple and culturally appropriate manner and prospective participants should be helped to arrive at an informed decision by use of appropriate language (grade 10 level- use Flesch Reading Ease Scores on Microsoft Word), selecting of a nonthreatening environment for interaction and the availability of peer counseling (Department of Health, 2004)

If the potential participant is unable to read/illiterate, then a right thumb print is required and an impartial witness, who is literate and knows the participant e.g. parent, sibling, friend, pastor, etc. should verify in writing, duly signed that informed verbal consent was obtained (Department of Health, 2004).

If anyone makes a mistake completing this document e.g. a wrong date or spelling mistake, a new document has to be completed. The incomplete original document has to be kept in the participant's file and not thrown away, and copies thereof must be issued to the participant.

References:

Balarane, A. 2015. *Determinants of livelihood strategies among smallholder farmers on irrigation schemes in the North-West Province, South Africa* (Doctoral dissertation, North-West University (South Africa), Mafikeng Campus), pp.108.

Department of Health: 2004. *Ethics in Health Research: Principles, Structures and Processes* <http://www.doh.gov.za/docs/factsheets/guidelines/ethnics/>

Department of Health. 2006. *South African Good Clinical Practice Guidelines*. 2nd Ed. Available at: http://www.nhrec.org.za/?page_id=14

DWA. (2007). *Berg Water Management Area, Proposal for the Establishment of the Berg Catchment Management Agency*. Developed in terms of Section 77 of the National Water Act, 1998 (Act No. 36 of 1998) for submission to the Minister of Water Affairs.

Frenken, K. (2005). Ed. *Irrigation in Africa in figures: AQUASTAT Survey*. Food and Agriculture Organization. Vol. 29, pp.74.

Appendix C: Ethics Approval Certificate

ETHICS APPROVAL CERTIFICATE

ETHICS APPROVAL CERTIFICATE

FACULTY OF SCIENCE, ENGINEERING AND AGRICULTURE
RESEARCH ETHICS COMMITTEE

NAME OF RESEARCHER/INVESTIGATOR: MBAIMBAI V

STAFF/STUDENT NO: 11640438

PROJECT TITLE: Hydrological modelling for estimating water availability for
irrigation supply in selected schemes in Nzhelele area

ETHICAL CLEARENCE NO: FSEA/18/HWR/11/1707

SUPERVISORS/ CO-RESEARCHERS/ CO-INVESTIGATORS

NAME	INSTITUTION & DEPARTMENT	ROLE
Dr Makungo	University of Venda, Department of Earth Sciences	Supervisor

Type: Student research

Risk: Minimal risk to humans, animals, or environment (Category 1)

Approval Period: June 2022-May 2023

The Faculty Research Ethics Committee (FREC) of the Faculty of Science, Engineering and
Agriculture hereby approves your project as indicated above.

General Conditions

While this ethics approval is subject to all declarations, undertakings and agreements
incorporated and signed in the application form, please note the following.

- The project leader (principal investigator) must report in the prescribed format to the REC:
 - Annually (or as otherwise requested) on the progress of the project, and upon
completion of the project



University of Venda

PRIVATE BAG X5050, THOHoyANDOU, 09505, LIMPOPO PROVINCE, SOUTH AFRICA
TELEPHONE (015) 962 3504/6313, FAX (015) 962 3080

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