



Application of SWAT hydrological model in a mine catchment in South Africa

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ABSTRACT

A comprehensive rainfall–runoff model was developed for the B11C–B11E study area, encompassing three quaternary catchments ($\pm 1\,330\text{ km}^2$). The aim was to effectively oversee a catchment area, ensuring the fulfilment of fundamental human requirements and promoting the sustainable use of water resources amidst the impact of mining activities. Additionally, the aim was to minimise adverse environmental effects, such as large-scale dewatering. The study area, located in the Mpumalanga province, falls within the Vryheid Formation, renowned for significant coal reserves. Over the past century, extensive mining activities have taken place in this catchment, directly impacting water resources through pollution and local resource depletion.

The choice of the Soil and Water Assessment Tool (SWAT) rainfall–runoff model was based on its effectiveness in simulating hydrological processes, especially in watersheds with limited data availability. The study area was divided into 15 sub-basins, and a Digital Elevation Model was employed to establish watershed boundaries, delineate sub-basins, define land use and soil data, and configure model parameters to ensure accurate representation of reality in the model.

Observed data, including rainfall, flow, and water quality data, were collected for 18 years (1991–2008), covering the period with available data for most flow and rainfall gauges. The catchment, hosting various land uses (urban, agricultural, and mining), underwent changes over this period. To model the impact of mining effectively, a literature-derived approach segmented the time series data into three periods: a reference period, a middle period, and a recent period.

In the calibration of the SWAT rainfall–runoff model, key parameters included runoff curve number, soil hydraulic conductivity, and deep aquifer percolation recharge. Calibration and validation were performed using the B1H021 flow gauge, located at the catchment outflow. The Nash–Sutcliffe Coefficient values of 0.73 and 0.77, along with coefficient of determination (R^2) values of 0.82 and 0.77, indicated a strong correlation between simulated and observed values.

The comparison of the reference and recent period models revealed shifts in the water balance influenced by weather fluctuations, conservation efforts, increased water usage, and mining impacts. Coal mining and other factors collectively contributed an average of $14.79 \times 10^6\text{ m}^3$ annually, indicating a notable increase in water consumption.

The study demonstrates that the SWAT model effectively simulates monthly runoff within the appropriate parameter range. While the model holds potential for future scenario analysis and water resource planning, caution is warranted.

The employed model in this study area provides a range of essential benefits for achieving the primary aim of effective management. It enables the prediction and simulation of various scenarios related to water resources, aiding decision-makers in anticipating changes, and to plan accordingly. The model facilitates the assessment of mining impacts on the hydrological system, supporting informed decision-making and targeted mitigation efforts. Decision-makers can optimise resource allocation, identify and manage risks, and conduct scenario analyses to understand the potential effects of different variables. Additionally, the model aids in long-term planning, community engagement, regulatory compliance, and fosters data-driven decision-making by relying on accurate hydrological representations. The continuous feedback loop ensures that real-time data would improve the accuracy of the model over time, enhancing the overall effectiveness of water resource management strategies.

The research successfully achieved its main aim of utilising hydrological modelling as a potential tool to explore the hydrology of a mining catchment in South Africa. The primary achievement was to provide valuable insights for water resource management in mining-affected areas.

Keywords: Rainfall-runoff model; quaternary catchment; mining activities; coal; water resources; SWAT; calibration; water resource management.

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LIST OF ABBREVIATIONS

95PPU	95% Prediction uncertainty
AGRR	Agricultural land-row crops
AWC	Available water capacity
CN2	Runoff curve number
DEA	Digital Earth Africa
DEM	Digital elevation model
DWS	Department of Water and Sanitation
ESCO	Soil evaporation compensation factor
FAO	Food and Agriculture Organization
FRSE	Forest-Evergreen
GIS	Geographic information system
HRU	Hydrological response units
NSE	Nash–Sutcliffe efficiency
NRCS	Natural Resources Conservation Service
P-factor	Percent factor
PAST	Pasture
PBIAS	Percent bias
R-factor	Relative factor
R ²	Coefficient of determination
RCHRG_DP	Deep aquifer percolation recharge fraction
SCS	Soil Conservation Services
SOL_AWC	Soil layer water holding capacity
SOL_K	Soil hydraulic conductivity
SUFI-2	Sequential Uncertainty Fitting version 2
SWAT	Soil and Water Assessment Tool
SWAT-CUP	Soil and Water Assessment Tool – Calibration and Uncertainty
Programs	
SWMM	Storm Water Management Model
USDA	United States Department of Agriculture
WRSIM 2000	Water Resource Simulation Model

NOMENCLATURE

%	Percentage
$10^6 \text{ m}^3/\text{m}$	Million cubic metre per month
$10^6 \text{ m}^3/\text{y}$	Million cubic metre per year
mamsl	Metre above mean sea level (a unit of depth)
mbgl	Metre below ground level (a unit of depth)
m^3/m	Cubic metre per month (a unit of volume)
m^3/y	Cubic metre per year (a unit of volume)
mm	Millimetre (a unit of length)
mm/a	Millimetre per annum (a unit of length per year)
MW	Megawatt

CHAPTER 1

INTRODUCTION

1.1 Background

Even though the Earth's surface is made up of over 70% of water, the total sum of freshwater found on the Earth's surface only makes up approximately 3% of the water supply, of which only 1% is easily accessible (Schmeier *et al.*, 2019). Water availability depends primarily on hydrological factors and can be impacted by natural conditions over time. While natural conditions such as droughts can cause water scarcity, it is often worsened by unsustainable land use, over-abstraction, intensified irrigation, deteriorating water quality due to contamination, and deforestation.

Mining is another factor that can deteriorate water availability, as it can influence both the quantity and quality of surface water and groundwater and make water unfit for use. The pollution caused by the mining industry can even affect areas with an abundance of water resources. Even though the mining industry has long been cautious of the risk associated with water, it still faces water resource management problems.

To better anticipate and understand water-related challenges, effective and efficient water resource management is of utmost importance when optimising the use of water resources. Hydrological modelling, and more specifically catchment hydrological modelling, has become a vital component in water resources management in South Africa. Hydrological models are frequently used in several applications of which a few include: the delineation of flood lines, predicting inflows for reservoirs, and assessing the potential impacts of climate change and land cover (Glenday *et al.*, 2022). There is an overabundance of modelling tools available, each with its own approach of representing hydrological processes. Taking into consideration the reliance on modelling to help inform important decisions, it is equally important that capacity building and research should continue. This will inevitably enable the water sector to make wise use of the number of tools and strategies presented by the models. This study will aim to contribute to this field by examining the hydrology of a mining impacted catchment in South Africa by means of a hydrological model.

1.2 Problem statement

Mining activities primarily impact the environmental medium of water in South Africa, alongside air (Department of Water Affairs and Forestry, 2006). Mining has negative impacts on the hydrological and topographical features of mining regions, presenting a considerable threat to the water resources of South Africa. The mining process imbalances the ecosystem, which consequently has

an effect on the hydrological cycle and rainfall. Other processes associated with mining activities such as the disturbance of drainage systems, reduction of soil moisture, deforestation etc., are also responsible for an unpredictable hydrological cycle and rainfall.

Mining will regularly have an impact on water resources through direct or indirect contact with ground and surface water. Hence, the environmental problems associated with mining activities are soil contamination, air pollution, land degradation, surface and groundwater pollution, degradation of forest and loss of biodiversity, decline in the functionality of the natural drainage system, noise, and vibrations. Perhaps the most noteworthy problem of all is its effects on water resources.

While coal mining is widely recognized for its significant impact on water quality, involving the degradation of water through diversion, consumption, and contamination (Olsson, 2013), the challenges and controversies within the realm of mining-affected river runoff and water resource management are multifaceted and require deeper exploration. One key challenge lies in understanding the complex interactions between mining activities and hydrological systems. Mining operations not only alter surface water flow patterns through the construction of infrastructure such as dams and reservoirs but also disrupt groundwater recharge processes through changes in land use and landscape modification. These alterations can lead to shifts in river runoff dynamics, including changes in flow rates, sediment transport, and nutrient cycling, with far-reaching implications for ecosystem health and water availability (Wolkersdorfer & Mugova, 2008). Furthermore, the management of water resources in mining-affected areas is often complicated by conflicting interests and stakeholder priorities. Local communities, environmental advocacy groups, government agencies, and mining companies frequently hold different views on water allocation, pollution control measures, and land use planning, leading to regulatory challenges and governance gaps. Addressing these conflicts requires interdisciplinary approaches that integrate ecological, social, and economic considerations into water resource management strategies (Kalogiannidis *et al.*, 2023).

Another contentious issue revolves around the long-term sustainability of water supplies in regions heavily reliant on mining activities. As coal reserves become increasingly depleted and extraction methods evolve, questions arise regarding the feasibility of continued water-intensive mining practices and their compatibility with broader environmental conservation goals. Balancing the economic benefits of mining with the need to safeguard water resources for future generations necessitates innovative approaches to water management, including water recycling, pollution mitigation technologies, and adaptive governance frameworks (Kalogiannidis *et al.*, 2023).

Recent observations indicate a notable decrease in river runoff systems, such as the Olifants River in the Mpumalanga Province, especially in regions extensively affected by coal mining (McCarthy, 2011). However, there exists a restricted pool of research that has effectively measured the elements

contributing to this phenomenon. Urgent attention is required to develop some methods for assessing the reasons behind the decrease in river runoff, ultimately guiding restoration efforts for river ecology. This study, focusing on the Steenkoolspruit, which serves as the most significant tributary of the Olifants River, examines the segment of this river located within three quaternary catchments, B11C–B11E, known for high mining impact. Located in the Mpumalanga Province, the research area is situated within the Olifants Water Management Area. Geographically, the area spans from 28° 57' E – 29° 27' E to 26° 07' S – 26° 31' S, and the altitude varies from approximately 1 709 mamsl upstream to 1 518 mamsl downstream. Kriel, the largest town in the study area, contains the world's richest coal deposits and is further expanding due to mining activities in the area (Banks et al., 2011). Hence, to effectively manage a catchment influenced by mining activities and minimize the negative environmental impact, the study area B11C–B11E, spanning three quaternary catchments, was identified. The choice of the study area is significant, given the fact that the Mpumalanga Province plays a vital role in providing South Africa with its coal, as over 60% of the province's land is either designated for mining rights or is currently under prospecting applications (Simpson, 2019). Hence, the suitability of the Soil and Water Assessment Tool (SWAT) model for assessment in a mining-affected catchment area is underscored by this feature, in conjunction with the specified study region.

1.3 Aim and objectives of the study

1.3.1 Aim

The term "mining catchment" denotes a geographical area where mining activities occur, exerting a substantial influence on the surrounding hydrological system. Encompassing the entire watershed affected by mining operations, from the water source to its downstream users, a mining catchment serves as the focal point of this study. The primary aim is to comprehensively investigate the impacts of mining on a catchment, particularly focusing on the hydrology of a mining catchment in South Africa through the application of a hydrological model.

Aligned with this objective, the study endeavours to advance knowledge in the field of water resources by examining how mining activities influence the hydrological processes within a catchment. By underlining the importance of effective water resource management, the study aims to illuminate the intricate interactions between mining and water resources, thereby guiding the adoption of sustainable management practices. Utilising a hydrological model, the research aims to analyse the dynamics of water flow, quality, and availability within the mining catchment. This holistic examination will deepen the understanding of the hydrological impacts of mining activities and facilitate the formulation of informed strategies for water resource management in mining-affected regions of South Africa.

1.3.2 Objectives

1. To develop a numerical rainfall–runoff hydrological model tailored to the specific characteristics of the mining catchment in South Africa.

Collecting relevant data on the mining catchment such as land use, geology, topography and hydrological parameters. Additionally, a crucial step in aligning with the objective is the careful selection and configuration of a suitable numerical model that can accurately represent the unique features of the mining catchment.

2. To calibrate and validate the hydrological model using observed data to ensure its accuracy and reliability.

Improve the model until it accurately represents the hydrological process within the mining catchment.

3. To simulate water flow within the mining catchment under different scenarios, considering variations in rainfall, land use, and other relevant factors.

Define the model scenarios by means of climate (rainfall patterns), land use, and any other relevant parameters. Run the model for each scenario to simulate flow within the mining catchment.

4. To evaluate the impacts resulting from alterations in land use patterns and variations in climate conditions on hydrological processes.

Simulating the hydrological processes under the different conditions to evaluate their effects on water resources.

1.4 Layout of the dissertation

Chapter 1: Introduction

The first chapter contains the introduction that includes the background, problem statement, and the aim and objectives. This chapter also outlines the structure and organisation of the dissertation.

Chapter 2: Literature review

The literature review encompasses details on water resources, mining catchments, and hydrological models. Previous studies related to mining catchments are reviewed, as well as identifying gaps in the literature. The theoretical background of numerical rainfall–runoff models is discussed as well as the criteria for model selection.

Chapter 3: Data and methods

The methodology is formulated from the literature review describing the suggested approach followed and supported by the literature review. It also details the specific methods employed for the data collection process, model development, calibration and validation. The scenario analysis is also discussed in the context of the study.

Chapter 4: Description of study area

This chapter introduces the study area and then sets the stage for a detailed description. This chapter provides a comprehensive description of the different elements that have an impact on the hydrology of the mining catchment, including land use patterns, climate conditions, and physical features.

Chapter 5: Hydrological modelling with SWAT

This chapter provides information on the importance of data analysis in the understanding of hydrological processes. The analysed data such as rainfall, flow, and land use will lay the foundations for consequent modelling.

The chapter further offers a detailed overview of the procedures utilised in modelling the designated study area. The model must be set up during multiple different stages. The subsections in this chapter describe these stages that are involved in the setup of the SWAT. The chapter further describes the execution of the rainfall-runoff model to simulate flow within a mining impacted catchment.

Chapter 6: Calibration and validation

The steps involved in the calibration and validation processes are outlined in this chapter. It describes the criteria used to evaluate model performance as well as the processes of manual and semi-automated calibration.

Chapter 7: Results and discussion

Chapter 7 analyses and presents the results obtained during the model calibration and validation processes. This also includes sensitivity and uncertainty analyses, the calibration results and the validation outcomes.

Chapter 8: Conclusions and recommendations

Chapter 8 is the last chapter and concludes the study and mentions a few recommendations that were noted during the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Water is essential for all life on earth, which explains why this resource is under enormous pressure. One of the most compelling issues South Africa is facing, both now and in the foreseeable future, is the availability of freshwater resources. The world possesses an ample supply of freshwater resources to fulfil the requirements of its inhabitants (Malley *et al.*, 2009). However, the problem South Africa is facing is the supply of well-maintained infrastructure to capture and hold freshwater, specifically in areas where there is freshwater supply (Dube & Van der Zaag, 2003).

Water sources around the world are facing global pressures because of the increase in population, which is anticipated to propel the globe towards a freshwater crisis before the year 2050 (Malley *et al.*, 2009). Climate change is one of the most significant, and perhaps misunderstood, risks that we are facing globally in the 21st century. According to Davis-Reddy and Vincent (2017), its impacts are one of the most pressing issues decision-makers are facing worldwide. The World Economic Forum released a report in 2015 (IISD, 2015) in which they stated that rising greenhouse gases, failure of climate adaptation, mismanaged urbanisation, extreme weather events, and food and water insecurity are identified as the most likely consequential risks that decision-makers are facing today. Freshwater availability and accessibility are known to attract social development and economic growth (Malley *et al.*, 2009). This is because the utilisation of freshwater resources has an influence on the greater part of all economic sectors of a nation (Rahm *et al.*, 2006).

The establishment of an industry such as mining contributes to economic growth, while social development includes people migrating to urban centres in search of employment. In 2021, South Africa's mining industry employed as much as 458 954 people (Garside, 2022). Figure 2-1 illustrates the active mining areas in South Africa. The global reliance on the mining sector is intertwined with its dependence on water resources; hence, it cannot be excluded from the equation of social and economic development. Sustainability is the vehicle and platform that must be utilised by the mining industry to emerge as influential leaders in the realm of responsible water management, not only in South Africa, but also in the world. Even though approximately 70% of the major mining companies worldwide are in areas classified as water stressed (Faul, 2018:9), they are such huge role players in the use of water resources and, subsequently, they contribute a sizable amount to the gross domestic product in South Africa (Faul, 2018:44). Hence, it is crucial for South Africa to sustain the industry within the bounds of responsible utilisation.

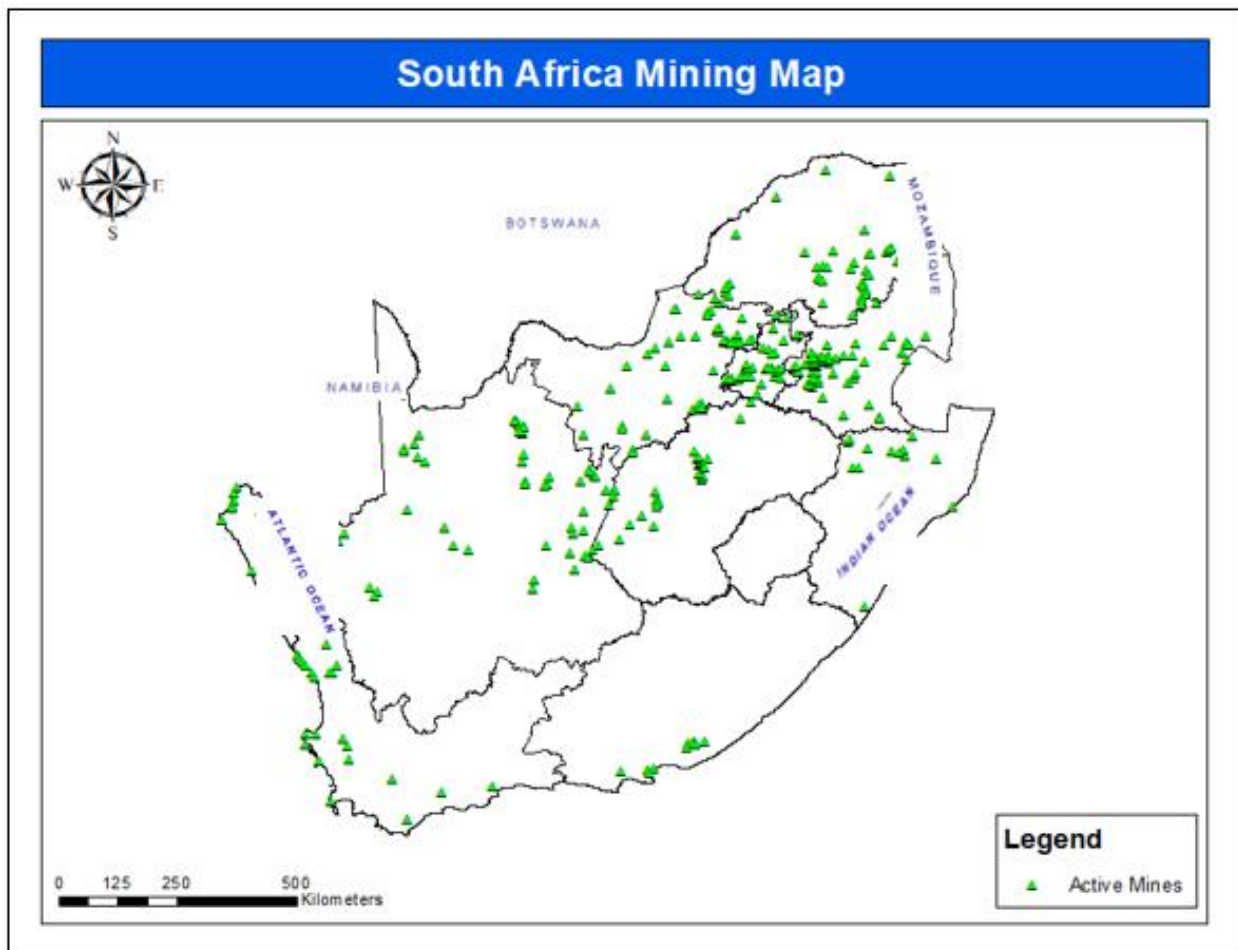


Figure 2-1 Active mining areas in South Africa (Adapted from Council of Geoscience, 2022)

South Africa's mining industry, with its vast amount of mineral resources, is the reason behind the wealth created, which has financed the development of the country (McCarthy, 2011). The extraction of these resources in the mining industry brings the benefit of employment opportunities for local people as well as other benefits to close communities. However, while it contributes significantly to South Africa's economy, it adversely impacts the environment (air, water, and land) and presents a long-term burden on the economy and a loss of valuable resources. According to McCarthy (2011), these long-term effects of mining are likely to be more severe in South Africa, because of ongoing global change. Global change drivers consist of a rising population expansion and its connected energy consumption, resource consumption, land use change, climate change and pollution (Vitousek, 1994). In some areas it can be expected that global change will decrease water provision and availability in ecosystem services (Schröter *et al.*, 2005:1333). Knowledge around freshwater resources must increase in order to predict the impact that global change factors will have on water supply. This essentially requires research that focuses on water management in mining regions. Building on the above statement by Gleick (cited by Ncube, 2006:12) means that the water crisis the world is facing stems from an insufficient comprehension and a deficiency in understanding how human activities alter the hydrological cycle and overall water resources. In the future, the scarcity

of water at a regional level is poised to become the reason for limiting development in multiple business sectors, including the mining sector. It is therefore encouraged that policy tools capable of managing the scarcity of water resources be established among competing sectors, and socio-economic planning be modified to implement water limitations (Ncube, 2006:12).

This demands a paradigm shift regarding water resource management to handle the highlighted issues, since the current management is incapable of providing sustainable solutions. According to Falkenmark and Chapman (1989), the key to effective and successful water management depends on studies identifying water-related issues and identifying solutions as well as hydrological data. In a region such as South Africa, where the demand on water resources is increasing, the need to understand hydrological systems becomes just as crucial, because it is the gateway to providing reliable information on the management of water resources.

Given the growing demand for water resources, it is crucial to address the linkage between water and land use such as mining because, ultimately, decisions related to land use also becomes water use decisions. Hydrology, more specifically operational hydrology, offers insight into the predictable hydrological characteristics of a specific site, the influence that man-made changes have, as well as the long-term foreseeable hydrological effects that human activities have (Ncube, 2006:12). It provides a holistic approach applicable to land and water resource management as well as the effect that land use has on partitioning rainfall into stream flow.

The mining industry's consumption of freshwater is small in proportion to the total water use in South Africa and even worldwide (Meißner, 2021:1). However, at local and regional scale, mining may have a consequential effect on freshwater resources, more specifically when environmental water requirements and limitations are considered and when water consumption in the area exceeds the amount of available water. In South Africa, where the availability of freshwater is very irregular, spatially and temporally, and where both human and financial resources available for long-term sustainability are inadequate, practical hydrological models and tools undertake great importance (Hughes, 2004).

2.2 Hydrological processes

Hydrological processes form the cornerstone of how water moves within a catchment, and it plays a pivotal role in forming the dynamics of water resources. These processes include a range of phenomena that regulates the circulation, distribution, along with the quality of water within the hydrological cycle. Most important among these processes are precipitation, infiltration, evaporation, runoff, and groundwater flow (Hussainzada & Lee, 2021).

Precipitation, in its various forms such as rain, snow, and hail, serves as the primary driver of the hydrological cycle by replenishing surface water sources and replenishing groundwater reservoirs. Evaporation and transpiration, collectively known as evapotranspiration, represent the loss of water back into the atmosphere, balancing the input of precipitation. Infiltration refers to the movement of water into the soil and underlying rocks, where it may contribute to groundwater recharge or surface runoff, depending on soil characteristics and land use (Thompson, 1999).

Surface runoff occurs when precipitation exceeds the infiltration capacity of soils or when the ground is saturated, leading to the flow of water overland and into streams, rivers, and the ocean. This runoff not only replenishes surface water bodies but also transports sediment, nutrients, and pollutants, influencing aquatic ecosystems and water quality (Lisetskii *et al.*, 2023). Groundwater flow, on the other hand, involves the movement of water through subsurface geological formations, sustaining baseflow in rivers and providing a vital source of water for drinking, irrigation, and industrial purposes (Thompson, 1999).

These fundamental hydrological processes characterise the behaviour of catchments and aids in predicting their responses to various environmental drivers, including land use changes, climate variability, and anthropogenic activities such as mining. In the context of mining-affected catchments, a comprehensive understanding of these hydrological processes is particularly pertinent, as mining activities can alter natural drainage patterns, disrupt groundwater flow regimes, and introduce contaminants into water bodies. Consequently, an appreciation of the fundamental hydrological processes is foundational to effectively assessing and mitigating the impacts of mining on water resources, ensuring the resilience and sustainability of catchment ecosystems and communities.

2.2.1 Hydrological processes in mining-affected catchments

Mining activities exert profound influences on hydrological processes within catchments, leading to significant alterations in both surface water and groundwater systems. These alterations, arising from changes in land use, landscape modification, and the introduction of contaminants, can have far-reaching consequences for water quantity, quality, and availability.

2.2.1.1 Surface Water Flow Alteration

One of the primary impacts of mining activities on surface water systems is the diversion of surface water around the mine site. This diversion is particularly pronounced in instances of trans-drainage basin diversion (Marcus, 1997, cited by Wolkersdorfer & Mugova, 2008), wherein natural surface water pathways are disrupted, leading to profound changes in runoff patterns and water distribution. Consequently, the creation of new water bodies, such as pit lakes and tailings ponds, further

complicates surface water dynamics, fundamentally reshaping catchment hydrology (Wolkersdorfer & Mugova, 2008).

Throughout the operational lifespan of a mine, various water sources generated by mining activities interact with surface water systems. These include pumped water, tailings dam effluents, and seepage from waste rock dumps. The introduction of these water sources into surface water systems following treatment protocols alters water quality and flow dynamics, impacting downstream ecosystems and water users (Wolkersdorfer & Mugova, 2008).

Seepage from underground workings, boreholes, inclines, or shafts represents another significant contributor to surface water alterations in mining-affected catchments. This seepage, often laden with contaminants, can infiltrate surrounding surface water bodies, leading to contamination and changes in flow patterns (Wolkersdorfer & Mugova, 2008).

As mining operations progress and excavated voids fill with groundwater, water begins to discharge into adjacent watercourses or terminal pit lake sinks (Karmakar & Das, 2012). This discharge significantly influences downstream flows and aquatic habitats, introducing new water sources and altering natural flow regimes.

Tailings dam water constitutes a substantial linkage between mining operations and surface water systems. Overflow, seepage into surrounding watercourses, and indirect discharge through groundwater pathways can all contribute to changes in surface water quality and flow dynamics downstream of mining activities (Fortuna *et al.*, 2021).

Waste rock generated by mining operations, if containing minerals prone to acid generation or elevated contaminant concentrations during weathering, can discharge seepage water that poses significant risks to receiving water bodies (Karmakar & Das, 2012). This seepage alters surface water quality and can lead to adverse ecological impacts downstream.

2.2.1.2 Groundwater Modifications

Mining activities have profound and multifaceted impacts on groundwater systems, exerting influence across various hydrological processes and ecological domains. As mines extract valuable minerals from beneath the earth's surface, they interact with and alter the intricate network of groundwater resources that underpin terrestrial ecosystems and human livelihoods (Wolkersdorfer & Mugova, 2008). From the lowering of water tables and subsidence caused by underground excavations to the reduction of moisture content in soil and the atmosphere, mining operations can induce significant changes in groundwater dynamics and hydrological cycles. Moreover, the disturbance wrought by mining activities extends beyond localised impacts, with repercussions on rainfall patterns, climate conditions, and broader environmental stability.

Mining operations often necessitate the dewatering of underground workings to facilitate extraction activities. This process involves the continuous pumping of groundwater from mine shafts and galleries to maintain safe working conditions. Consequently, the sustained extraction of groundwater results in the lowering of the water table in surrounding areas (Tomiyaama & Igarashi, 2022). This phenomenon can lead to the depletion of aquifers, reduced availability of water for local communities and ecosystems, and potential long-term impacts on groundwater recharge rates (Karmakar & Das, 2012).

Subsidence is a common consequence of underground mining activities, particularly in areas where extensive extraction occurs. As mining activities progress, the removal of subsurface material can lead to the collapse or settling of overlying strata, resulting in ground subsidence (Lee & Abel, 1983). This subsidence can disrupt natural groundwater flow patterns, causing changes in aquifer characteristics and potentially altering the connectivity between surface water and groundwater systems. Additionally, subsidence poses risks to infrastructure integrity and can exacerbate surface water drainage issues (Lee & Abel, 1983).

Mining activities can contribute to the reduction of moisture content in both soil and the atmosphere through various mechanisms (Zhang *et al.*, 2022). Excavation activities, such as open-pit mining and quarrying, can disturb soil structure and lead to increased surface evaporation, reducing soil moisture levels. Additionally, the disturbance of vegetation cover and the creation of barren landscapes can further exacerbate soil drying processes. Furthermore, the release of dust and particulate matter into the atmosphere from mining operations can contribute to the drying of the air, potentially affecting local microclimates and atmospheric moisture levels (Zhang *et al.*, 2022).

Mining activities can disrupt the natural hydrological cycle, rainfall patterns, and local climate conditions through various direct and indirect mechanisms (Jhariya *et al.*, 2016). The alteration of surface water flow patterns, such as diversion and impoundment for mine water management purposes, can disrupt the natural distribution of water within catchments, potentially leading to changes in rainfall patterns downstream (Karmakar & Das, 2012). Moreover, the release of dust and aerosols into the atmosphere from mining operations can affect cloud formation processes and precipitation dynamics, altering local rainfall patterns and contributing to changes in regional climate conditions over time. Additionally, the modification of land surfaces and landscapes through mining activities can further influence local climate by affecting surface albedo, heat absorption, and evapotranspiration rates, thereby exacerbating temperature extremes and climate variability (Jhariya *et al.*, 2016).

2.2.1.3 Contaminant Transport

Contaminant transport represents a critical aspect of the environmental impacts associated with mining activities within catchment areas. As mining operations progress, various contaminants are mobilised and transported through surface and groundwater systems, significantly altering water quality and ecosystem dynamics (Jhariya *et al.*, 2016). Mining operations generate a variety of pollutants, including heavy metals, metalloids, acidity, and suspended solids, which can leach into surrounding water bodies through runoff, seepage, and groundwater flow (Ugya *et al.*, 2018). These contaminants pose risks to human health, aquatic ecosystems, and water quality, requiring diligent monitoring and mitigation measures to prevent adverse impacts on downstream users and ecosystems.

Among the most prevalent contaminates is acid mine drainage (AMD), a consequence of sulphur-bearing minerals exposed during mining oxidising and releasing acidic and metal-rich runoff into water bodies (Ugya *et al.*, 2018). This process poses significant risks to both aquatic ecosystems and human health, underscoring the urgency of understanding and addressing contaminant transport mechanisms.

Additionally, sedimentation from mining activities can aggravate water quality degradation by increasing turbidity and sediment loads in water bodies (Ugya *et al.*, 2018). Soil erosion from disturbed landscapes, coupled with sediment runoff from mine sites and waste dumps, leads to elevated sedimentation levels in rivers and streams. Such sediment transport not only affects channel morphology but also heightens flood risk and disrupts aquatic habitats, further compromising water quality within catchment areas (Ugya *et al.*, 2018).

Moreover, mining activities can disrupt nutrient cycling processes within catchment areas, further aggravating water quality concerns (Hu *et al.*, 2023). Runoff from mine-affected areas often carries elevated concentrations of nutrients, such as nitrogen and phosphorus, into water bodies. These excessive nutrient inputs can trigger eutrophication, fostering algal blooms, oxygen depletion, and disruptions to aquatic ecosystems.

Importantly, the cumulative effects of multiple mining operations within a catchment can aggravate hydrological alterations and compound environmental risks. Mining activities can profoundly alter surface and groundwater systems, affecting water flow patterns, water quality, and ecosystem dynamics within the catchment area. By examining how mining operations influence hydrological processes, such as runoff, infiltration, and groundwater recharge, researchers can delineate the boundaries of a mining catchment and assess its hydrological connectivity to surrounding water bodies. This interdisciplinary approach integrates hydrological science with mining engineering

principles to define the spatial extent and hydrological behaviour of a mining catchment, informing water management strategies and environmental impact assessments.

2.3 Mining Catchment

Balasubramanian (2017) describes a mine as a site where minerals, metals, or other valuable geological materials are extracted from the earth through excavation, drilling, or other methods. Mines can vary widely in size, scale, and type of operation, ranging from small-scale artisanal mines to large-scale industrial operations.

On the other hand, a catchment, also known as a watershed or drainage basin, refers to an area of land that is drained by a common river system or body of water. It is defined by the topographical divide, such as hills or mountains, that separates it from adjacent catchments. Precipitation that falls within a catchment area eventually flows into streams, rivers, lakes, or groundwater systems, shaping the hydrological processes and influencing water availability and quality within that area.

In the context of mining, a mine catchment refers to a geographical area where mining activities occur and have a significant impact on the surrounding hydrological system. In a mine catchment, the extraction of mineral resources, such as coal, metals, or minerals, alters the natural flow of water, affects water quality, and can lead to changes in ecosystem dynamics.

Mining catchments exhibit several key characteristics that distinguish them from other geographic areas. Firstly, they are marked by the presence of mining operations, both active and historical, which encompass various extraction methods such as open-pit and underground mining (Balasubramanian, 2017). Associated infrastructure, including waste rock dumps, tailings storage facilities, and processing plants, further delineates these catchments. Moreover, mining activities within catchments often disrupt the natural hydrological connectivity between surface water and groundwater systems (Jhariya *et al.*, 2016). Excavation, dewatering, and stream diversions are common practices that alter water pathways and flow dynamics. Consequently, mining catchments frequently experience significant impacts on water resources, manifesting as changes in quantity, quality, and availability. Acid mine drainage, contaminated runoff, sedimentation, and modified drainage patterns are among the water-related consequences observed in these areas. Additionally, the environmental footprint of mining extends beyond water resources, leading to habitat degradation, soil erosion, and loss of biodiversity. To address these concerns, regulatory frameworks govern mining operations within catchments, implementing permits, monitoring requirements, and environmental assessments to mitigate adverse effects and promote sustainable resource management (Balasubramanian, 2017).

2.4 Types of mining activities in coal mines

Knowing the geographical and hydrological boundaries of a mining catchment helps provide context for the various mining operations that take place within it. In general, coal mining activities primarily involve both underground and surface mining methods, tailored to the geological characteristics of coal deposits and the economic feasibility of extraction (Balasubramanian, 2017). Below are the main types of mining activities commonly practiced in coal mines in South Africa:

2.4.1 Underground Mining

Underground mining delves deep beneath the earth's surface, requiring intricate tunnelling systems and shafts to access mineral deposits buried at significant depths. This method is often employed when valuable minerals are located far below the surface, necessitating specialised equipment and safety measures to navigate the complex underground environment. Techniques such as bord-and-pillar mining and longwall mining are commonly utilised to extract minerals efficiently while minimising the risk of cave-ins or collapses. While underground mining offers access to rich deposits that may be otherwise unreachable, it also presents formidable challenges, including high operating costs, logistical complexities, and safety hazards inherent in working underground (Balasubramanian, 2017). The following is a list of underground mining techniques practiced in South Africa.

Bord-and-Pillar Mining

This method, also known as room and pillar mining, is widely used in South Africa for extracting coal from underground deposits. It involves the creation of a network of rooms and pillars within the coal seam, with the pillars providing support for the roof (Oosthuizen, 2005). Bord and pillar mining is suitable for coal seams with moderate thickness and stability.

Longwall Mining

Longwall mining is employed in some South African coal mines, particularly for thick and continuous coal seams. This highly mechanized method involves the extraction of coal along a long face using a shearing machine, with hydraulic supports providing roof control (Jurd, 1977). Longwall mining allows for high production rates and efficient coal recovery

Cutting Machines

In certain instances, cutting machines are used for selective underground mining in South African coal mines. These machines are equipped with cutting drums or picks to extract coal from the seam, allowing for precise control over the mining process and minimizing waste generation (Balasubramanian, 2017).

2.4.2 Surface Mining

Conversely, surface mining operates closer to the earth's surface, employing open-pit mines, quarries, or strip mines to extract minerals from shallow deposits spread across expansive areas (Balasubramanian, 2017). This method is favoured when mineral resources are located near the surface, making them economically feasible to extract using heavy machinery and equipment. Surface mining techniques involve the removal of overlying soil, rock, and vegetation to access the desired minerals, with excavators, bulldozers, and trucks being key components of the extraction process. While surface mining generally incurs lower operational costs and poses fewer safety risks compared to underground mining, it can have significant environmental consequences, including habitat destruction, soil erosion, and water contamination (Balasubramanian, 2017). Striking a balance between resource extraction and environmental conservation is essential in mitigating the ecological impacts of surface mining activities. The following is a few of the surface mining techniques practiced in South Africa.

Open-pit Mining

Open-pit mining is a common surface mining method employed in South Africa for extracting coal from shallow deposits. Large open pits are excavated using heavy equipment, such as draglines, excavators, and trucks, to remove overburden and expose the coal seam. Once exposed, the coal is mined and transported to processing facilities (Minerals Council South Africa, 2022).

Strip Mining

Strip mining is practiced in South Africa for coal seams that are relatively shallow and continuous over large areas. Overburden is removed in sequential strips using earth-moving equipment, allowing access to the underlying coal seam. The coal is then extracted and hauled to the surface for processing (Gordon, 2023).

Auger Mining

Auger mining is a specialized surface mining technique used in South Africa for extracting coal from near-surface deposits. It involves the use of a rotating auger drill to penetrate the coal seam and extract coal through a continuous flight conveyor. Auger mining is suitable for thin coal seams and areas where conventional mining methods are impractical (Follington *et al.*, 2001).

2.5 Mining impacts on water resources

Expanding upon the insight provided in Section 2.2.1 mining activities can have significant impacts on water resources, leading to alterations in water quantity, quality, and availability.

Mining operations often necessitate significant water usage for various activities like ore processing, dust suppression, and infrastructure cooling (Hamaraoui *et al.*, 2024). This heightened demand for

water can result in the depletion of local water sources, particularly in arid or water-scarce regions, impacting both surface water bodies and groundwater aquifers. Groundwater extraction may cause damage to streamside habitats located several kilometres away from the actual mining site.

An examination of data sourced from the US Geological Survey (USGS) and the World Resources Institute's (WRI) Aqueduct Water Risk Atlas highlights the prevalence of critical mineral mines, deposits, and districts situated in areas experiencing high or extremely high baseline water stress (Lakshman, 2024). In these regions, at least 40% of the annual water supply is required to fulfil existing demand, leading to intense competition for water resources among agricultural, industrial, and domestic users, often leaving insufficient water to support vital freshwater ecosystems (Lakshman, 2024).

Furthermore, approximately 8% of global critical mineral sites are in arid or low-water-use regions where available water supplies and total water demand are notably limited (Lakshman, 2014). The escalation of mining activities in these areas could escalate water demand and escalate water stress levels, exacerbating the strain on already scarce freshwater supplies. Arid, low-water use, and/or highly water-stressed countries hosting critical mineral sites include the United States, Australia, South Africa, India, China, Mongolia, Russia, Mexico, Chile, and Namibia (Lakshman, 2014). Research also shows that water stress is rising in many areas of the world, underscoring the importance of not only considering water quantity but also considering the impact on water quality due to extensive usage of water in mining operations and the resultant strain on water resources.

Mining activities can introduce pollutants into water bodies, leading to significant impacts on water quality. Acid mine drainage (AMD) is a notable consequence of mining operations, with diverse effects on both groundwater and surface water resources (Ugya *et al.*, 2018). The acidic nature of AMD renders water unsuitable for various purposes, including domestic use, irrigation, and livestock watering, as well as for aquatic habitats. Additionally, AMD generation often results in increased turbidity in receiving water bodies due to the formation of iron (III) hydroxide, commonly known as yellow boy. The suspended solids present in AMD-affected water, whether originating from the site or transported by flowing water, reduce light penetration, adversely affecting aquatic organisms (Gonah, 2016).

Furthermore, the physical effects of acidic water on water resources become evident when it interacts with carbonate aquifers, particularly dolomite and limestone aquifers. This interaction leads to the dissolution of rock particles, creating solution holes that can result in land subsidence and the formation of sinkholes. Such phenomena pose risks to productive aquifers and can lead to the loss of streams, especially in areas with karst topography. When streams disappear into the subsurface, ecosystem disturbances occur, impacting riverine ecosystems and riparian zones. Consequently, both groundwater and surface water resources are adversely affected in regions dominated by

carbonate rocks, exacerbating contamination risks as large openings and sinkholes facilitate rapid water movement within the groundwater system (Gonah, 2016).

Mining activities can alter natural hydrological processes, affecting the availability of water downstream. For example, the construction of dams, reservoirs, and diversion channels for mining purposes can disrupt natural flow regimes, leading to reduced water availability for downstream users and ecosystems (Hamaraoui *et al.*, 2024). These changes in water quantity, quality, and availability resulting from mining activities can have adverse effects on aquatic ecosystems. Reduced flow rates, habitat degradation, and contamination can harm aquatic flora and fauna, leading to declines in biodiversity and ecosystem health (Gonah, 2016). Furthermore, mining-related alterations to water resources can also impact nearby communities that rely on water for drinking, agriculture, and other purposes. Water contamination and reduced availability can pose health risks and economic challenges for local populations, particularly in rural or indigenous communities dependent on natural water sources.

Overall, mining impacts on water resources highlight the importance of implementing sustainable mining practices and robust environmental management strategies to minimise adverse effects and safeguard water quality and availability for present and future generations.

2.6 Water resource management

Water resource management (WRM) plays a crucial role in ensuring the sustainable use and protection of water resources, particularly in regions affected by mining activities. The United States Agency for International Development (USAID) (2021) defines WRM as a process that includes strategic planning, construction, and oversight of water resources to ensure their sustainable use in terms of quality and quantity, catering to the needs of both human societies and ecosystems. WRM includes the organisational structures, economic incentives, physical infrastructure, along with data managing systems that facilitates effective decision-making and implementation of water management strategies.

A significant challenge in WRM arises from the fact that water transcends political and administrative boundaries, connecting various landscapes and environments, both natural and built-up environments. This interconnectedness extends across land, sea, and sky, encompassing mountainous, inland, and coastal regions. Given water's pivotal role in social, economic, and environmental spheres, reconciling diverse and often conflicting demands for freshwater presents a critical yet intricate task (UNEP, 2012). Decision-making processes regarding water management must acknowledge this interdependence to avoid unintended repercussions, such as heightened conflicts and insecurities. For instance, in response to climate change, authorities may consider constructing dams to strengthen water storage for future use during periods of scarcity. However,

without robust stakeholder engagement and coordinated planning, such initiatives may exacerbate water stress upstream and downstream, elevate flood risks, and trigger displacement (UNEP, 2012). Moreover, alterations in land use within upper watersheds can significantly influence downstream flood probabilities and water availability, impacting rapidly expanding urban centres. Active involvement of stakeholders across various water uses and basins in WRM can substantially mitigate overall risks associated with floods and droughts, fostering resilient and sustainable access to water for all.

The need for effective decision-making tools in navigating water-related challenges can be contributed by hydrological models. By actively engaging stakeholders and leveraging hydrological models, WRM initiatives can better anticipate and manage water-related risks, enhancing resilience and sustainability.

2.6.1 The contribution of hydrological models

Hydrological modelling, a key tool in water resource management, offers valuable insights into the dynamics of water systems, enabling stakeholders to make informed decisions and develop effective management strategies. According to Wheeler (cited by Hussainzada & Lee, 2021), a hydrological model is a simplified representation of a real-world system that consist of several equations or a logical set of operation within a computer program.

Hydrological models play a crucial role in water resource management and environmental impact assessment. These models facilitate various tasks such as analysing input-output relationships within a basin, estimating runoff for ungauged areas, forecasting the effects of basin changes like land use or climate change, integrating hydrology with geochemistry or meteorology, and even contributing to global climate models (Hussainzada & Lee, 2021).

Hydrological models have the capability of estimating the amount of water available within a catchment area (Thompson, 1999). This information is crucial for planning water allocation, especially in regions facing water scarcity. They can predict the likelihood and severity of floods by simulating rainfall-runoff processes, which in turn allows authorities to implement appropriate measures in terms of flood prevention or emergency response planning. Wheeler *et al.* (2007) mean that hydrological models can be used together with water quality models to determine the transport of pollutants within water bodies. This helps to identify contaminated water sources, evaluating the effectiveness of mitigation measures and the protections of water quality for human consumption and ecosystems. Hydrological models have the ability to simulate the potential impact of climate change on water sources, including temperature, precipitation patterns, droughts and floods (Hughes, 2004). This information is essential for the development of adaptation strategies which aids in the mitigation of climate change on water availability and quality. Hydrological models can assess

groundwater recharge rates, aquifer dynamics, and the interactions between surface water and groundwater. This information is essential for sustainable groundwater management, preventing overexploitation, and maintaining ecosystem balance (Weather *et al.*, 2007). They can evaluate hydrological impacts of land use changes, such as deforestation, urbanisation, or even agricultural expansion. By the quantification of infiltration, runoff and evaporation, these models help to inform land planning decisions that minimize adverse effects on water resources.

Hydrological models serve as valuable tools for understanding the complex dynamics of water systems and supporting informed decision-making processes in water resource management.

2.6.2 The contribution of hydrological models in a mining affected catchment

Water is essential for the profitability of the mining sector, yet its unsustainable use and pollution during operations can adversely affect local communities and ecosystems. Consequently, the mining industry faces a triple mandate for sustainable water management, motivated by economic, environmental, and social considerations. As pressures to improve efficiency and reduce the environmental impacts of mining, hydrological models can be used to facilitate better water use and ensure compliance with environmental norms.

Hydrological models simulate the movement of water within catchment areas, allowing for the estimation of water availability under different climatic, land use, and management scenarios (Keller *et al.*, 2023). In mining-affected catchments, where water resources may be impacted by mining activities, hydrological modelling helps assess the quantity and quality of available water, aiding in sustainable water allocation and planning. They can predict the potential impacts that mining activities can have on water resources, which includes changes in surface water flow, groundwater levels, along with water quality. By simulating different mining scenarios and their associated hydrological responses, stakeholders can anticipate and mitigate adverse impacts, such as water pollution, depletion, and flooding, in mining-affected catchment areas (Weather *et al.*, 2007).

Keller *et al.* (2023) mean that hydrological models enable risk assessment and decision support in water resource management by quantifying uncertainties and evaluating the potential consequences of management decisions. In mining-affected catchment areas, where risks such as acid mine drainage, sedimentation, and groundwater contamination are prevalent, hydrological modelling provides valuable insights for risk mitigation and adaptive management. They can facilitate the evaluation of various water management strategies aimed at mitigating the impacts of mining on water resources (Keller *et al.*, 2023). By simulating the effectiveness of measures such as water conservation, pollution control, and land rehabilitation, stakeholders can identify cost-effective and environmentally sound approaches to water resource management in mining-affected catchments.

Hydrological modelling supports long-term planning and adaptation in water resource management by simulating future hydrological conditions and assessing the resilience of water systems to environmental change (Hussainzada & Lee, 2021). In mining-affected catchment areas, where mining activities may have lasting impacts on water resources, hydrological modelling helps identify sustainable management practices and adaptive strategies for safeguarding water security and ecosystem integrity. Hydrological modelling facilitates stakeholder engagement and collaboration in water resource management by providing a common platform for sharing data, information, and perspectives (Weather *et al.*, 2007). In mining-affected catchment areas, where multiple stakeholders, including mining companies, local communities, regulatory agencies, and environmental organizations, have vested interests, hydrological modelling supports participatory decision-making processes and conflict resolution.

2.7 Hydrological modelling

Hydrological models are widely used as an effective tool to establish a relationship between hydrological processes and environmental parameters and to estimate future impacts on hydrology (Sakhaee, 2021). Hughes (2004) defined hydrological models as "mathematical representations of the processes involved in the transformation of climate inputs such as precipitation, solar radiation and wind, through surface and subsurface transfers of water and energy into hydrological outputs (typically, flow in rivers, soil moisture content or water levels in ground-water aquifers)". The primary objective of hydrological modelling is to gain knowledge and an understanding of the hydrological process. This means providing reliable data and information to manage water resources in a maintainable manner to protect the environment and to increase the well-being of humans (Hughes *et al.*, 2003). In the past few years, hydrological models have been employed for the formulation of strategies in managing water resources, and to determine the effect that deforestation, land use, climate and water use will have on watershed management (Getachew & Melesse, 2012). Furthermore, it has also become the tool for common decision-making and planning (Arnold *et al.*, 1998).

Hydrological models existed as early as the 1930s. They were originally developed as event-based models, which operated on hand calculations (Weather *et al.*, 2007). Developments in computational power in the 1960s allowed hydrological models to run continuous simulations, and in so becoming more conceptually complicated, in other words, physically-based (Hughes, 2004; Weather *et al.*, 2007). The latest hydrological models incorporate mathematical algorithms that represent a real-world hydrological and physical process. Concurrently, with an increase in computer power it allows for more powerful methods to run analysis of models and to indicate the uncertainty related to hydrological simulations (Weather *et al.*, 2007). For an intricate environment, such as a mining catchment, this can be beneficial.

However, the application of hydrological models, and more specifically physically-based models, are not without difficulty. A more complex model means more parameters. Weather *et al.* (2007) defined a parameter as a measurable factor that forms part of a set of characteristics that stays constant under certain conditions. Physically-based models are based on the representation of individual processes such as groundwater drainage, infiltration, evapotranspiration, interception, and groundwater movement, which consequently involves more parameters. Multiple parameters need to be quantified by a model to reach a solution, consequently these models require better resources in terms of effort, time, and information (Hughes, 2004). The question arises of whether mathematical algorithms that are invented by laboratory studies, can adequately represent hydrological processes which in real life operates on a much larger scale (Beven, 1989; Hughes, 2004). For these models to produce reliable and adequate results, the model developer must understand the interaction of hydrological processes, and then be able to translate these interactions into mathematical equations, namely model algorithms (Hughes, 2004).

Hydrological models can further be described as spatially and temporally complex. Spatially complex models, as described by Hughes (2004), disaggregate the total modelled area into multiple smaller areas, based on geometric shapes such as polygons and square grids, and natural drainage units, such as catchments, slopes, and channels. In terms of temporal complexity, for example, the model uses either hourly or daily inputs while the simpler models are based on monthly time intervals. A more complex model, which will either contain multiple parameters or are temporally and spatially complex, will require data of a greater quantity or quality. This can be problematic in a mining catchment, which contains multiple parameters, and may consequently lead to a lack of quality in the data (Taleb *et al.*, 2021:1).

Hughes (2004) explained that the increase in computational power has removed any obstacles to developing and applying complex models. However, the problem now lies with the ability of the modeller to provide the information these models need. The problematic lack of data quality, as previously mentioned, can be potentially solved by applying a Geographic Information System (GIS). The application of a GIS system allows hydrological models to be more user-friendly. By using techniques that utilise GIS to interface a model with data, and even a broader utilisation and implementation of remote sensing, future models will be less restricted by data. Even so, users should be mindful of the limitations when hydrological models are practically applied. This is emphasised by Xu and Singh (1998) when they stated that the modeller is constantly faced with a choice between a sophisticated model with incomplete data or a less complex model for which the data requirements are not as strict.

2.7.1 Rainfall–runoff models

A diverse range of rainfall–runoff models is available globally with different built-in capabilities and intended uses. Nevertheless, identifying the right and most suitable model for the relevant application can pose a challenge. Hydrologists acknowledge that achieving a close fit between observed and simulated runoff data in a rainfall–runoff model is insufficient. Simply achieving this does not accurately reflect the replication of the underlying hydrological process (Uhlenbrook *et al.*, 2003).

The characteristics of the hydrological model determine the specific input data that is required for running the model. Two types of input data are essential, namely data that drives the simulation and data for estimating parameters. A parameter is represented by a value that characterises the physical attributes of the hydrological system, establishes initial conditions for the components, or serve as a constant rate for various processes. There are two categories of model parameters – process parameters, which establish initial conditions for components (e.g., flow rates), and physical parameters, which portray the physical structure of the model (e.g., catchment area and channel length) (Thompson, 1999).

Certain models are more sensitive to specific parameters. A sensitivity analysis can indicate which parameters are particularly sensitive to changes in values. This involves a simulation run with different parameters and comparing the results to discern which parameter will influence the overall outcome more. If an output shows minimal change, then a parameter value is changed, and the model is deemed less sensitive to the specific parameter (Thompson, 1999).

This study constituted a part of a larger study aimed at developing a water management model tailored for the identified catchment. The hydrological model should be able to seamlessly assess the long-term impact of land use practices on water resources, making it well-suited for studies in water resource management. The rainfall–runoff model should be able to demonstrate versatility across different spatial scales, from large river basins to small watersheds, enabling its application to a range of hydrological modelling scenarios. It is essential that the model should exhibit proficiency in simulating hydrological processes even in watersheds where data availability is limited.

There is a variety of hydrological models available for a hydrologist to choose from. For the purpose of the study, only hydrological models that incorporate a mining component were considered. This criterion was integral to the model selection since the chosen model should be able to process the necessary features and capabilities in order to effectively simulate all the intricacies associated with mining in the watershed.

The following is a brief description of the hydrological models that was considered for the study:

2.7.1.1 Water Resource Simulation Model (WRSM 2000)

Pitman *et al.* (2008:viii-ix) described the WRSM 2000 model as follows:

WRSM 2000 is a mathematical model to simulate the movement of water through an interlinked system of catchments, river reaches, reservoirs, irrigation areas and mines. WRSM 2000 is of a modular construction (running under Windows), with five different types of module (runoff, reservoir, irrigation, channel and mine) linked by means of routes. The routes represent lines along which water flows, such as river reaches.

WRSM 2000 has been used to analyse the hydrology on a monthly time scale for various applications that include calibration of streamflow records taking land use changes over time into consideration by comparing observed flows against simulated flows; regional assessment of water resources; the production of naturalised flow records; to estimate flows in ungauged catchments, for simple reservoir yield analysis; input to complex system models of water resources; input to water quality studies and input to ecological water requirement models.

WRSM 2000 is totally modular. Each of the five modules contains one or more hydrological models that simulate a particular hydrological aspect. The modules are linked to one another by means of routes. Multiple instances of different modules, together with the routes, form a network. By choosing and linking several modules judiciously, virtually any real-world hydrological system can be represented.

WRSM 2000 simulates flows in a catchment and by comparing against observed flows, the user can analyse statistics and graphs of various water resource parameters and manipulate calibration parameters to achieve a good fit between observed and simulated flows. The model is not appropriate for flood design and for determining yields of dams in a complex system of competing water users.

2.7.1.2 Storm Water Management Model (SWMM)

Rossman (2010:1,2) described the SWMM model as follows:

The EPA [Environmental Protection Agency] Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub-catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprises of multiple time steps.

SWMM accounts for various hydrologic processes that produce runoff from urban areas. These include: time-varying rainfall; evaporation of standing surface water; snow accumulating and melting; rainfall interception from depression storage; infiltration of rainfall into unsaturated soil layers; percolation of infiltrated water into groundwater layers; interflow between groundwater and the drainage system; nonlinear reservoir routing of overland flow; capture and retention of rainfall/runoff with various types of low impact development.

Spatial variability in all of these processes is achieved by dividing a study area into a collection of smaller, homogeneous sub-catchment areas, each containing its own fraction of pervious and impervious sub-areas. Overland flow can be routed between sub-areas, between sub-catchments, or between entry points of a drainage system.

SWMM also contains a flexible set of hydraulic modelling capabilities used to route runoff and external inflows through the drainage system network of pipes, channels, storage / treatment units and diversion structures. In addition to modelling the generation and transport of runoff flows, SWMM can also estimate the production of pollutant loads associated with this runoff.

2.7.1.3 Soil and Water Assessment Tool (ArcSWAT)

Janjić and Tadić (2023:331-333) described the ArcSWAT hydrological model as follows:

The SWAT model was developed at the US Department of Agriculture. A GIS interface was developed to aid in its efficient development. These interfaces make it easier to assess the impact of various watersheds and water management scenarios and to assess water quality. However, this model has its own limitations.

The SWAT model was developed to quantify the impact of management in large and complex watersheds with different soil types, land uses, and management conditions over a long period. The model is semi-distributive, with the option of working on monthly or daily time steps. The latter is recommended for the best output results. SWAT can estimate the relative effects of different management scenarios on water quality, sediment, and agricultural chemical yields in large, ungauged catchments. The components of the sub-catchment model can be divided into hydrology, weather, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Simulated hydrologic processes include surface runoff estimated using the SCS curve number or Green–Ampt infiltration equation; percolation modelled with a layered storage routing technique combined with a crack flow model; lateral subsurface flow; groundwater flow to streams from shallow aquifers; potential evapotranspiration by Hargreaves, Priestley–Taylor, and Penman–Montecito methods; snowmelt; transmission losses from streams and water storage; and losses from pounds.

Three key sets of data are required to set up a SWAT model: topography data (digital elevation model, DEM), land use cover, and soil data. In addition to data on topography, land use, and soil, meteorological data are very important to us for running the SWAT model simulation. The hydrologic cycle is conditioned by the climate and provides moisture and energy inputs, such as daily precipitation, maximum and minimum air temperatures, solar radiation, wind speed, and relative humidity, which control the water balance. SWAT model can read these data directly from the files, and, if something is missing, it can be generated using the SWAT model generator.

2.7.2 Model selection criteria

According to Asl-Rousta *et al.* (2017), the selection of a hydrological model is centred around the capacity of the model to simulate water quality processes and hydrology in each catchment and, secondly, to provide accurate results when compared to the measured results to confirm the effectiveness of the model. Given the multiple rainfall–runoff models that exist, the choice of a model for a specific scenario is rarely a simple one. Thus, the model selection is inevitably based on data availability, economic constraints, and personal preference along with simply hydrological considerations (Beven & O'Connell, 1982). The criteria guiding the selection of the model are outlined in Table 2-1.

Table 2-1 Criteria for model selection

Criteria	Motivation
Operability with limited data	The model should be able to operate effectively even when faced with a data-scarce watershed
GIS integration	Allowing the data preparation to be easier and enhance spatial analysis
Readily available model	The model should be readily available to all users
A model with an active user community and support	This will help to facilitate user assistance and troubleshooting
Simulate water flow within the mining catchment under different scenarios	Purpose of the study
Support a fully distributed physically-based model	The model should be able to provide a detailed representation of the physical characteristics of the catchment, which will assist in the modelling of complex hydrological processes
Semi-distributed model offering flexibility with time-step options	Semi-distributed models offer a compromise, providing a balance between accuracy and computational efficiency. Whereas a daily time-step may provide optimal, more detailed output results.
Uncertainty and parameter calibration	Functions for batch runs, uncertainty, parameter sensitivity and calibration of the model

A concise review of hydrological models for catchment analysis was performed to identify a suitable model for the research. The initial choice for the study was the SWMM. During the model conceptualising phase, it was noted that SWMM lacked an integrated GIS component. Knowing how significant a GIS-based interface is in effortlessly translating digital land use, soil, and topographical data into model input, the model was consequently excluded as a possible option.

Further research led to the considerations of the WRSW 2000 model. But limitations were identified, which included a limited linkage to land cover processes, as well as the inclusion of multiple land cover types. Given the significant impact of land cover, in particular mining, in the catchment, this raised a concern. Additionally, the WRSW 2000 model lacked the model capacity for uncertainty analysis, parameter sensitivity and calibration. As these capabilities were essential, it was therefore decided to use the ArcSWAT model.

Although ArcSWAT was developed in the northern hemisphere, it has been successfully used in multiple studies in South Africa as mentioned in section 2.9. Models that have been developed locally can hold advantages from being designed with the local data availability and local climate characteristic of South Africa in mind. SWAT has the advantage of a resource development team on the back end that continually updates and adapts the model to utilise developing global data that include remotely sensed data.

The ArcSWAT hydrological model was chosen for its specific capability in evaluating the effects related to land management practices, such as mining, in a complex watershed. The study area,

characterised by diverse land use practices that effects the rainfall–runoff relationship, makes it particularly suitable. ArcSWAT is a free model, and the availability of user support significantly enhances the utility of the model. The model has been developed for over 30 years, which resulted in several interfaces, tools, and support software. This model addresses channel ecological and surface terrestrial processes, studies water quality and quantity, and climate change, offering simulations and analyses across multiple different temporal scales. ArcSWAT is complemented by the SWAT Calibration and Uncertainty Program (SWAT-CUP) by providing different functionalities that include sensitivity analysis, calibration, validation, as well as uncertainty analysis.

However, the built-in local parameter database of the model is focused on Northern American vegetation and soil types, posing both a positive and negative aspect. While it has a built-in database that can assist when there is limited data available for the catchment, it requires scientists in South Africa to meticulously obtain and process land cover and soil databases for accurate application.

According to Glavan and Pintar (2014), there are opportunities beyond the SWAT model that enables it to grow and change in the future. Many environmental problems, as a consequence of mining, industrial and land use policies, caused the government to implement stricter legislation, which in turn encourages the use of a model such as SWAT.

In a study area with a long history of mining, it is clear that mining has had a significant impact on water quality and quantity. Hence, the application of the SWAT hydrological model in this mining-impacted catchment can provide valuable information for watershed management and the restoration of it.

2.8 SWAT model advantages and disadvantages

The SWAT model is a comprehensive hydrological model used to simulate water, sediment, and agricultural chemical transport in watersheds. Developed by the United States of America (USDA) Agricultural Research Service, it's widely employed in environmental studies, land management, and watershed management projects (Glavan & Pintar, 2014). It is a physically based semi-distributed hydrological model that facilitates the computation of water balance elements across spatial and temporal dimensions, generating runoff and sediment outputs within basins (Colín-García *et al.*, 2024). Primarily, its function revolves around estimating water availability within a given basin. The SWAT model's versatility extends to its applicability in various geographic regions and scales, allowing for tailored analyses of watershed systems globally. However, the model has some advantages and disadvantages as described in Table 2-2.

Table 2-2 Advantages and disadvantages of the different processes in SWAT (Glavan & Pintar, 2014)

Process	Advantage	Disadvantage
Hydrology	It is a comprehensive model that represents hydrological processes, including groundwater, surface runoff, and streamflow routing. It integrates spatial variability in topography, land use, and soil to capture watershed-scale dynamics. It is capable of simulating the effects that land management practices have on hydrological response, such as land use changes or conservation measures.	The model requires detailed input data on land use, soil properties, and topography, which may not always be accurately represented or readily available. Highly variable environments or data scarce study areas poses a challenge for the calibration of hydrological parameters. It may require significant computational resources for large-scale watershed simulations.
Land use	It allows for the representation of spatial variability in land use and land cover patterns within a watershed. It integrates changes in land cover and land use over time, by facilitating assessments of land use change impact on water quality and hydrology. It provides flexibility in terms of the simulating the effects of different land management practices, which include deforestation, urbanisation, or agricultural.	It faces challenges in accurately characterising land use dynamics, especially in heterogeneous or rapidly changing landscapes. The model is sensitive to classification schemes and input data resolution, which can have an influence on the model performance and uncertainty.
Soil	It accounts for soil heterogeneity and its influence on infiltration, water movement, and retention. It provides insights into soil erosion and sediment transport processes, aiding in erosion control and soil conservation planning.	It requires precise characterisation of soil properties, which may vary temporally and spatially. It is sensitive to model assumptions and input parameters, particularly in areas with complex land management practices or soil types.
Weather data	It incorporates climate data to steer hydrological and agricultural processes, allowing for assessments of climate change impacts. It can use historical weather data or generate synthetic weather sequences for long-term simulations. The model provides flexibility to assess the sensitivity of model outputs to variations in climate inputs.	It relies on spatial resolution weather and data accuracy, which may vary depending on interpolation methods and data sources. The ability to capture localised climate phenomena and extreme weather events is limited. Simulating future climate scenarios is challenging due to uncertainties in climate projections and downscaling techniques.
Streamflow routing	It simulates the behaviour of water through the stream network, considering channel storage, channel routing, and flow dynamics. It provides estimates of streamflow at different locations within the watershed, aiding in water resources management and flood forecasting. The effects of watershed characteristics are incorporated on streamflow generation and routing.	The models' representation of streamflow processes is simplified, such as floodplain interactions, backwater effects, and transient flow conditions. It relies on resolution and input data accuracy especially for representing streamflow observations, channel geometry, and flow routing parameters. Calibrating streamflow routing parameters and validating model outputs, especially in data-scarce or ungauged watersheds, is challenging.

2.8.1 Parameter and data requirements

ArcSWAT is a physical based model and therefore it requires extensive physical parameters to represent the real hydrological processes in the catchment scale. Parameters and data requirements are crucial for setting up and running ArcSWAT simulations accurately, ensuring that the model captures the complex processes governing watershed behaviour.

According to Emam *et al.* (2017) in hydrological modelling a parameter is a numerical value which is used to characterise the behaviour of different processes in the ArcSWAT model. The parameters are an important element to the representation of physical properties, coefficients, rates, or any other factor that has an influence on the model simulation behaviour of water, pollutants, nutrients, and sediments in the watershed.

In ArcSWAT, the hydrology processes simulate multiple aspects of water movement in the watershed, from groundwater flow, surface runoff, streamflow routing and infiltration. Parameters such as groundwater storage coefficients, initial abstraction ratio, channel routing, and Manning's roughness coefficients for overland flow are important for accurately representing this process (Arnold *et al.*, 2012a). Additionally, factors like the baseflow recession rate (ALPHA_BF), minimum groundwater flow threshold (GWQMN), and streamflow routing parameters enhance the model's capability to predict water availability and streamflow behaviour. Data requirements for the hydrology process include a DEM for topographic information, land use data, soil data, as well as meteorological data for driving the hydrological process and calibration/validation purposes.

The soil processes are a crucial components of watershed modelling, and several parameters play key roles in representing soil characteristics and behaviour. Alongside essential parameters like the Curve Number (CN) and soil hydraulic conductivity (SOL_K), additional parameters such as the soil erodibility factor (K-factor), soil bulk density, soil organic carbon content, soil pH, and soil texture fractions (sand, silt, clay) provide further insights into soil erosion, water retention, nutrient availability, and infiltration rates (Arnold *et al.*, 2012a). These parameters collectively contribute to a more comprehensive representation of soil processes within the model, facilitating accurate simulation of water movement and sediment transport across the landscape. The soil data requirements for soil processes include soil survey data or soil maps providing soil properties, soil erosion data including rainfall erosivity and soil erodibility, and land use data for assigning soil parameters to different land use types.

Weather data inputs are vital for driving hydrological processes and assessing the impacts of climate variability on watershed dynamics in ArcSWAT. In addition to standard meteorological variables like rainfall, temperature, humidity, and wind speed, incorporating parameters such as solar radiation, dew point temperature, barometric pressure, wind direction and speed, and snowmelt coefficients

enhances the model's ability to simulate evapotranspiration, precipitation patterns, and snowmelt runoff (Arnold *et al.*, 2012a). These weather parameters capture the complex interactions between atmospheric conditions and hydrological responses, enabling more robust simulations of water resources availability and management strategies. Data requirements for weather processes include historical weather data or climate datasets covering the simulation period and spatially distributed weather data if available, otherwise data from nearby weather stations.

Land use processes in ArcSWAT encompass a range of parameters that characterise land use types, agricultural practices, and urbanisation effects within the watershed. In addition to parameters like irrigation application efficiency and crop coefficients, including parameters such as the urbanisation factor, forest canopy interception factor, and land use change rates allows for a more refined representation of land use dynamics and their impacts on hydrological processes (Arnold *et al.*, 2012a). These parameters inform simulations of water demand, land use change scenarios, and the effectiveness of land management practices in mitigating water-related issues. Data requirements for land use processes include land use data representing the current landscape and historical land use data if simulating land use change scenarios.

Streamflow routing parameters are essential for accurately simulating the movement of water through the stream network and predicting streamflow behaviour in ArcSWAT. Alongside parameters like channel roughness coefficients and channel width and depth, including parameters such as channel slope, reach routing parameters, and infiltration excess runoff coefficients refines the model's representation of channel hydraulics, flow velocities, and routing processes (Arnold *et al.*, 2012a). These parameters contribute to more accurate predictions of streamflow volumes, velocities, and timing, supporting informed decision-making for water resources management and flood mitigation strategies. Data requirements for streamflow routing processes include stream network data including streams, rivers, and drainage channels and channel geometry data such as cross-sectional profiles and channel width.

2.9 Previous studies in similar context

The SWAT model has been employed globally to simulate hydrological processes in numerous hydrological studies. Abbas *et al.* (2018) attempted to quantify the influence of climate change on water resources in the Tigris River in Iraq and found that the SWAT model provides reasonable predictions of the impact of climate change on water resources. As another example of SWAT application, Qi and Grunwald (2005) modelled four sub-watersheds in a catchment in Ohio and found that the simulated trends match reasonably well with observed data. Future land use and climate change in the Zilbier River basin in Iran were assessed using SWAT and provided reasonable predictions of why the watershed will experience more pronounced effects from climate change in comparison to alterations in land use (Andaryani *et al.*, 2019).

2.9.1 The SWAT model in SA

Many studies in South Africa have been conducted using the SWAT model, either to evaluate land use on hydrological processes and water resources or to determine the applicability of the SWAT model to a specific area. Nevertheless, there is a scarcity of research both in South Africa and globally that concentrates on mining catchments. Moreover, only a handful of studies explicitly utilised the SWAT model as a management tool in the context of mining catchments.

Singo (2018) investigated the applicability of SWAT in assessing the impact of land use and land cover changes on hydrology and water resources within the Luvuvhu River catchment in Limpopo. While mining activities were briefly addressed, the study primarily focused on predicting runoff generation locations within the sub-catchment, demonstrating the suitability of the SWAT model for such analyses.

Similarly, Perry (2014) employed SWAT in a mountainous catchment east of the Blyde River Canyon in South Africa. The study revealed the model's satisfactory performance in simulating runoff in the mountainous terrain and highlighted its potential for application in similar ungauged catchments with comparable climate and land use patterns. Similarly, a study in KwaZulu-Natal aimed to calibrate the SWAT model for a well-researched catchment, emphasizing its suitability for evaluating hydrological changes resulting from land management practices such as the removal of exotic commercial species from wetlands and buffer areas (Querner & Van Zanen, 2013).

Despite its potential, the implementation of SWAT in South Africa is not without challenges. One significant issue highlighted across studies is the lack of locally relevant input data. The standard land cover characteristics included in SWAT are primarily based on conditions in the USA, which may not accurately represent the complexities of South Africa's landscapes. Consequently, several studies opted to use the default SWAT land use classes due to data limitations. Additionally, the complexity and data demands of the SWAT model pose obstacles, as it requires extensive calibration and validation processes that may be challenging in data-scarce environments.

The implications and patterns identified from these studies underscore both the potential and limitations of SWAT in South Africa. While the model holds promise for a wide range of applications, including water resource management and agricultural innovation analysis, its effective implementation requires addressing data deficiencies and adapting the model to suit local conditions. Furthermore, the complexity of SWAT necessitates careful consideration of its various capabilities and limitations, with many studies only utilising a fraction of its functionalities due to the challenges associated with comprehensive model calibration and validation.

Overall, while SWAT offers a valuable tool for assessing hydrological processes and land management impacts in South Africa, its successful application hinges on overcoming data

limitations, adapting the model to local contexts, and carefully navigating its complexity to fully leverage its capabilities for addressing water resource challenges and promoting sustainable development in the region.

CHAPTER 3

DATA AND METHODS

3.1 Introduction

The selection of the ArcSWAT rainfall–runoff model was discussed in the previous chapter, with specific reference to reasons behind the choice of model. This chapter discusses the methodology followed to implement aspects related to the creation of the ArcSWAT rainfall–runoff flow model for the identified catchment area. This section provides a description of the suggested methodology to follow, and the relevant input data required for the setup and running of the ArcSWAT model in the study area. The quality of input data for the SWAT model is fundamental, because ultimately the results that the model generates depend on the quality of the inputs; therefore, highlighting how important it is to spend time on data collection and processing.

The first step in applying ArcSWAT to the identified catchment involves the gathering and organisation of permanent data relevant to the study area. This encompasses geospatial data such as a DEM, land use and soil, as well as the meteorological data. Considering that ArcSWAT incorporates a built-in local parameter database primarily focused on Northern American land use and soil types, it became imperative to reconsider the classification of the land use and soil classes. Subsequently, the division of sub-watersheds and allocation of hydrological response units (HRUs) occur, a prelude for ArcSWAT before modelling.

To effectively enable ArcSWAT to model the impact of mining on the catchment, considering the role of mining and other anthropogenic activities in influencing the short-term quality and quantity of river runoff, a specific approach was derived from the literature. This approach involves dividing the time series data into three periods: a reference period, a middle period, and a recent period. By modifying some parameters, a runoff model based on SWAT was derived for the recent period of the study area; from this, the spatial and temporal distribution of runoff for each designated period could be extracted.

This study broadly utilised the following approach:

- a) Establish, calibrate, and validate the SWAT model for Steenkoolspruit river–runoff during the reference period.
- b) Integrate recent meteorological data into the existing SWAT model. The disparity between the simulated values for the two periods is regarded as the water reduction attributable to weather-related factors.

- c) Apply land use data from the recent period to the SWAT model. The difference in simulated values signifies the water reduction resulting from soil and water conservation measures. In this study, it is assumed that these measures are accurately represented by land cover data.
- d) Assess the recent period by comparing measured values with simulated values for runoff. The difference is considered to be the water reduction caused by factors other than weather and conservation measures. By subtracting the increased industrial and domestic water consumption, the remaining reduction is attributed to coal mining and other relevant factors.

Figure 3-1 illustrates the step-by-step process for calculating water reductions associated with different factors. Through the adjustment of specific parameters, a SWAT runoff model was derived for the study area during the recent period, enabling the determination of spatial and temporal runoff distribution.

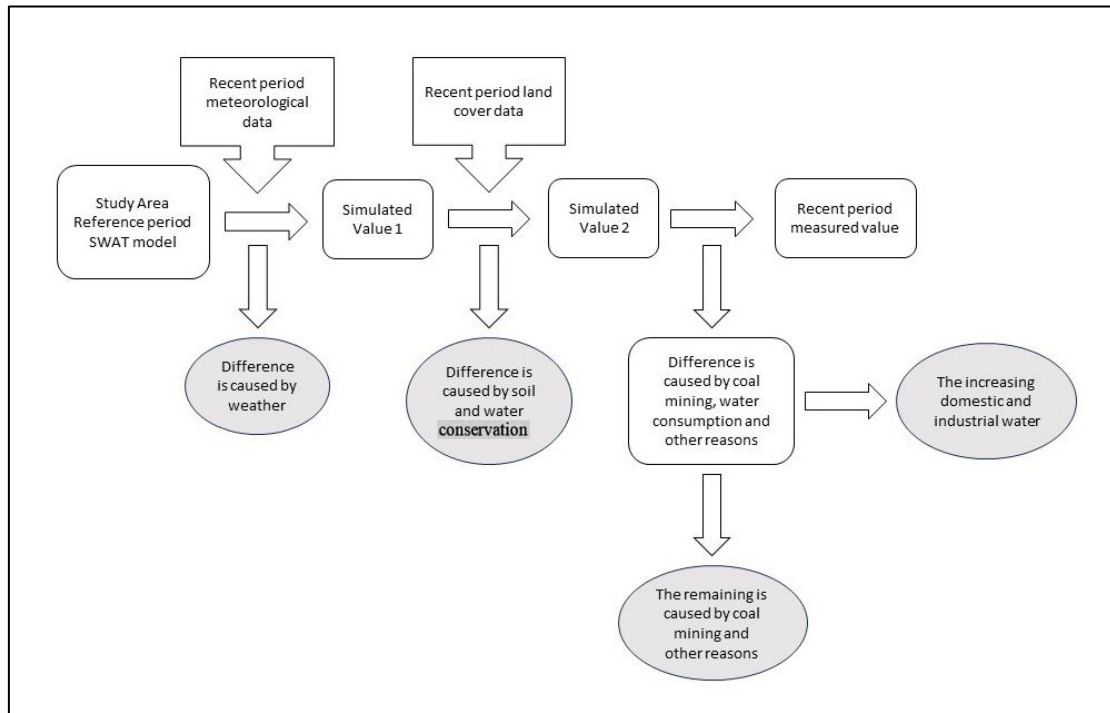


Figure 3-1 The process of determining water reductions linked to various factors
(Author's own, 2024)

A more comprehensive methodology is outlined in the subsequent section.

3.2 ArcSWAT model process

The ArcSWAT model is a powerful tool for watershed modelling, which allows users to simulate hydrological processes, land, and water management practices, and how it impacts water resources. The following section provides an overview of the ArcSWAT model process, as well as the impact that each selection process can have on the potential outcome.

3.2.1 Study Area Selection

During the study area selection process, the first step is to define the study area, which would typically be a watershed or a river basin, where the model will be applied. Part of the study area selection in ArcSWAT involves defining the boundaries of the watershed based on the natural drainage patterns. Considerations during the selection include hydrological characteristics, hydrological significance, scale, data availability, variability, stakeholder engagement, as well as iterative refinements. Accurate selection ensures that the modelling is representative and that it supports informed decision-making when it comes to water resource management.

The proper selection of a study area that includes these features along with the study area delineation ensures that the model captures relevant hydrological processes and land management practices specific to the watershed, leading to more accurate simulation results.

3.2.2 Data collection and preprocessing

Integral to the model setup and calibration, data collection forms a fundamental aspect. The SWAT model necessitates several inputs, including elevation data in the form of DEM of the quaternary catchment, geographical data, weather data (climate), and streamflow data. The DEM data must be in a raster file that is in a grid format required by the Environmental System Research Institute (ESRI). The SWAT model necessitates uniform projection for all input data, without specifying a particular projection. All the datasets that were used in this study was projected to Universal Transverse Mercator, using the 1984 World Geodetic System.

The required geographical data includes soil and land cover data that were either in shapefiles or grid files. The climate data involved temperature and daily rainfall data, which also included the locations of the temperature and precipitation gauges, formatted specifically for SWAT in a text file. The values for all these parameters can either be read into the model from observed data records or it can be generated

Additionally, according to Arnold *et al.* (2012a) the weather generator function within ArcSWAT aids in hydrological modelling, creating synthetic weather data for simulations. It uses statistical methods to mimic historical weather patterns and requires input data like precipitation and temperature records. After calibration and validation, weather series for specific time periods and locations can be generated. The tool enables uncertainty analysis and has applications in climate change assessments and water management. However, it has limitations, including simplifications in representing complex atmospheric processes. Therefore, results should be interpreted cautiously, and model constraints should also be considered.

High quality input data and preprocessing in the ArcSWAT model are critical for accurate model simulations. Errors or inconsistencies in input data can lead to biased simulation results and unreliable model predictions. The data collection and preprocessing lay the groundwork for the ArcSWAT model setup and hydrological modelling.

3.2.3 ArcSWAT setup

ArcSWAT, which is an extension for ArcGIS, is a geographical interface that simulates the processes within the SWAT model. Figure 3-2 shows a flowchart of the setup of the SWAT model by illustrating which datasets would be included in the model and at what point will they be introduced. The model setup involves identifying the watershed boundaries, land use, sub-basins, management practices and soil types.

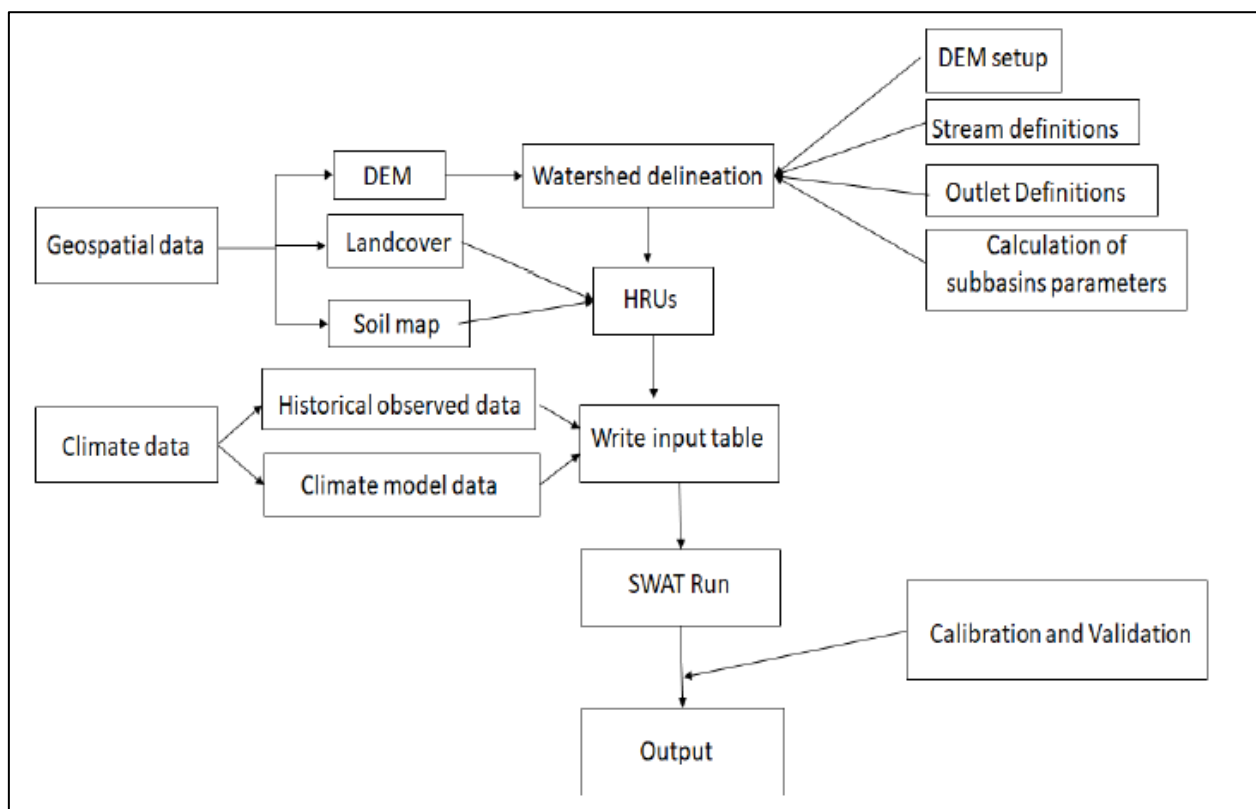


Figure 3-2 SWAT model flow chart (Author's own, 2024)

The land use, soil, and slope classes within the study area are also defined. To optimise the ArcSWAT setup, the built-in local parameter database of ArcSWAT is utilised, focusing on Northern American land use, vegetation, and soil types. Parameters are adjusted as necessary for the specific study area, which is followed by the division of the study area into sub-watersheds as well as the allocation of hydrological response units within these sub-watersheds.

3.2.3.1 *ArcSWAT (South American) database in a South African context*

The built-in database in ArcSWAT provides standardised land use classes and parameters for worldwide applications, which aims to streamline the model setup process and assist in comparisons between different regions. Conversely, the South African context may represent unique characteristics applicable to only South Africa, such as soil types, specific land use practices, and hydrological processes, which differ from those presented in the ArcSWAT built-in database.

The utilisation of the ArcSWAT built-in database has a potential impact on South African study areas, particularly in its capability to correctly represent local conditions and sufficiently capture the complexities of the watershed. It can cause inaccuracies and biases in the model simulation if the built-in database does not adequately align with the characteristics of the study area. An example would be inaccuracies in soil properties or land use classifications which can influence the estimation of hydrological processes, such as runoff. Also, discrepancies between local conditions and the built-in database can potentially limit the model's capability to provide reliable insights and predictions for water resources management and decision-making in South Africa.

While the ArcSWAT built-in database offers standardisation and convenience, its use in a South African context may require careful consideration of its applicability and potential limitations. Substituting the built-in database with locally derived data or customising parameters to better reflect regional characteristics can improve the accuracy and reliability of model simulations, ultimately enhancing the utilisation of ArcSWAT for watershed management in South Africa. One way of enhancing the model accuracy and customising parameters to better represent regional characteristics is to subdivide the study area into smaller sub-watersheds.

3.2.3.2 *Subdividing the study area*

According to Alsilibe and Bene (2022) during watershed modelling, it is beneficial to subdivide into sub-watersheds or into smaller units for modelling purposes. Each individual sub-watershed is presumed to be homogenous. However, the subdivision of a watershed influences the homogeneity since larger sub-watersheds tend to have more variable conditions. Increased effort for the preparation of input data is required when it comes to smaller sub watersheds. The impact that the subdivision of watersheds has on model simulations can be directly tied to the source of uncertainty, including soil types, land use, stream channels, sub-watershed topography, and climate inputs (Goodrich, 1992).

As part of the setup process in ArcSWAT, it is important to consider how the study area can be subdivided into manageable spatial units, such as HRUs or as sub-basins. There is multiple approached of subdividing the study area, each having its own impact on the model performance and outcomes. Table 3-1 describes the different subdivision types along with the impact thereof.

Table 3-1 Different ways of subdividing the study area and the implication of each (Aisilibe & Bene, 2022)

Subdivision	Description	Impacts
Hydrological subdivision	The study area is subdivided based on hydrological characteristic such as drainage pattern, topography, and flow accumulation.	This approach ensures that each sub-basin presents a different hydrological unit with homogeneous characteristics, which will allow for a more accurate simulation of hydrological processes. However, it may result in an uneven distribution of HRUs and computational complexity in areas with complex terrain.
Land use subdivision	The study area is subdivided based on land use, which could include agricultural fields, urban areas, forests, and water bodies.	This division apprehend the spatial heterogeneity of land use practices along with their influence on hydrological processes. It allows for targeted analysis of the impacts of land management practices on water resources. However, it may oversimplify the representation of hydrological connectivity and interactions between different land use types.
Soil subdivision	Soil types or soil properties, such as texture, erodibility and permeability cause the division in the watershed.	This will typically account for the influence of soil characteristics on water infiltration, runoff generation, and erosion processes. It enables more accurate simulation of soil-water interactions and sediment transport. However, it requires detailed soil data and may increase model complexity.
Geographical subdivision	Subdividing the study area based on geographical or administrative boundaries, such as watersheds, political units, or catchments.	This approach facilitates spatial organisation and management of model inputs and outputs. It allows for comparisons between different geographical units and alignment with existing management frameworks. However, it may overlook inherent hydrological variability within larger administrative units and hinder detailed analysis at smaller scales.
Custom subdivision	The study area is subdivided based on user-defined criteria or objectives, such as conservation priorities, water quality hotspots, or monitoring locations.	This allows for a more flexible approach to tailor the subdivision to specific research questions or management objectives. It allows for targeted analysis of areas of interest and customisation of model inputs. However, it requires careful consideration of the relevance and representativeness of the custom subdivisions.

By delineating the watershed during one of the initial steps in the ArcSWAT model setup, the study area was effectively subdivided into hydrologically district units which can then be further analysed and modelled.

3.2.4 Running the model

After the preprocessing of the data and before the running of the ArcSWAT model the temporal division process for modelling is done, which involved dividing the time series data into distinct

periods, such as a reference period, a middle period, and a recent period. This temporal division helps in understanding and capturing changes over time. To modify the ArcSWAT parameters for each period, insights are derived from literature, which particularly emphasises the influence of mining and various human activities on the quality and quantity of river runoff.

The next step is running the ArcSWAT model for each designated period to simulate runoff, accounting for the influence of mining and other anthropogenic activities on the hydrological processes within the catchment. The generated output is analysed to derive spatial and temporal distributions of runoff across the study area.

3.2.5 Model calibration

The calibration process of the SWAT model confirms that the model accurately represents the hydrological processes in the catchment. This involves the adjustment of model parameters so that it matches observed hydrological data. Effective calibration improves the model's ability to replicate observed hydrological behaviour, enhancing confidence in its predictive capabilities and the reliability of simulation results.

In this study two different calibration approaches were used, first manual calibration and secondly semi-automated calibration with SUFI-2 (Sequential Uncertainty Fitting version 2). Employing both calibration methods offers several advantages, such as complementary strengths, robustness and confidence, time, and resource efficiency, as well as flexibility and adaptability (Arnold *et al.*, 2012b).

Manual calibration allows for user intervention as well as expert knowledge which guides the calibration process. Manual calibration can especially be useful in situations where the user has great knowledge and insight into the hydrological processes of the study area. The semi-automated method has the complementary strength of providing a systematic framework where parameter uncertainty can be explored and allows for the search of optimal solutions in the parameter space. The SUFI-2 method quantifies the uncertainty related to the model predictions (Arnold *et al.*, 2012b).

When using both approaches, researchers have the opportunity to cross-validate the calibration results. If both approaches join on similar parameters and model performance, this increases the confidence in the calibrated model.

In terms of time and resource efficiency manual calibration can be time consuming specifically in large study areas or complex models. Whereas semi-automated calibration accelerates the calibration process with its capability of exploring the parameter space. It is beneficial to combine both approaches in this instance since the strengths of each method can be used while the overall time and calibration efforts are potentially reduced.

Since manual calibration are more flexible by incorporating knowledge, certain study areas or scenarios may benefit more from it. In contrast, when dealing with complex parameter interactions or large-scale studies, semi-automated calibration such as SUFI-2 allows for the exploration of parameter space, which is more suitable in large scale scenarios.

Manual calibration:

During the manual calibration process the user iteratively adjusts the model parameters according to the level of expertise and judgement. Parameter values are selected manually whereafter the model is run and evaluated against the observed data results, and the parameters then gets adjusted accordingly.

While this approach allows for direct user control and flexibility, it can be subjective and time consuming. Additionally, it may not systematically explore the parameter space like the semi-automated calibration, which in turn can lead to suboptimal solutions.

Semi-automated calibration with SUFI-2:

SUFI-2 is a widely used semi-automated calibration method that is implemented in the SWAT-CUP tool, which forms part of the ArcSWAT interface. It employs an uncertainty framework which means that parameter uncertainty quantified through repeated model simulations utilising a wide range of parameter values. The SUFI-2 algorithm iteratively adjusts the parameters based on the sensitivity of the model outputs to those parameters and the likelihood of achieving a good fit to observed data. It generates a parameter range which represents the uncertainty in model predictions because of parameter uncertainty (Arnold *et al.*, 2012b).

In the research SUFI-2 is a popular choice among semi-automated calibration methods, particularly because it efficiently explores the parameter space, it provides a framework for the quantification of parameter uncertainty, it provides flexibility and adaptability, and it provides a user-friendly interface for tuning calibration solutions.

Both calibration approaches offer many advantages and limitations, but it remains important to note that no calibration method is universally superior, and the choice of method was primarily based on the specific characteristics of the study area, available data, modelling objectives, and user preferences.

3.2.6 Sensitivity analysis

Sensitivity analysis delves into understanding the model's response to variations in its parameters. Sensitivity analysis plays an important role in both the calibration and validation stages of ArcSWAT modelling.

Before or during the calibration process, whether it is manual calibration or semi-automated calibration, sensitivity analysis is conducted which helps to assess the influence that the model parameters can have on the model outputs. Sensitivity analysis helps identify which parameters have the most significant impact on model predictions and which parameters may require adjustment during calibration. Sensitivity analysis is often an iterative process that occurs throughout the entire research process, from model setup to calibration to validation. As insights are gained into parameter sensitivity and model behaviour, the modelling approach are adjusted, parameter ranges are defined, or certain parameters are prioritised for further investigation or refinement.

In this study sensitivity analysis was performed during the manual calibration and during the semi-automated calibration processes. The methodology followed for model calibration in this study closely adhered to conventional practice, as outlined by Balascio (cited by Moriasi *et al.*, 2007). Initially, manual calibration was conducted in ArcSWAT by comparing simulated outputs, such as streamflow, with observed data for the same time period. This process involved gaining a thorough understanding of the model structure and prioritizing key parameters based on their impact on the variable of interest, informed by expert insights and sensitivity analysis. Parameter ranges were defined, and nine parameters crucial for hydrological processes were manually adjusted until satisfactory R^2 values and visual flow patterns were achieved. Initially, only R^2 was considered due to its simplicity, but as calibration progressed, sensitivity analysis revealed the importance of multiple evaluation techniques. Through an iterative process involving hundreds of iterations, the top six parameters, identified as most sensitive, were selected for further semi-automated calibration. Section 6.4 discusses the process in more detail and the results are illustrated in Section 7.1.

In the SUFI-2 methodology, sensitivity analysis involves two main aspects: global sensitivity analysis and one-at-a-time sensitivity analysis.

3.2.6.1 Global sensitivity analysis

The global sensitivity approach simultaneously evaluates the sensitivity of model outputs to variations in all parameters. It considers how changes in multiple parameters interact to affect model predictions, providing insights into parameter interactions and overall model behaviour. Global sensitivity analysis helps identify which parameters have the most significant influence on model performance across the entire parameter space (Arnold *et al.*, 2012b).

3.2.6.2 One-at-a-time sensitivity analysis

Arnold *et al.* (2012b) means that on-at-at-time, also known as local sensitivity, assesses the sensitivity of model outputs to variations in each parameter individually, while keeping other parameters constant. It isolated each parameter and then evaluates the impact, which allows for the understanding of the relative importance of each parameter. However, one-at-a-time sensitivity analysis does not capture potential interactions between parameters, which may lead to incomplete or biased sensitivity assessments.

Therefore, global sensitivity analysis was performed in this study as part of the SUFI-2 calibration process. It considers interactions between parameters, providing a more comprehensive assessment of parameter sensitivity and model behaviour.

The global sensitivity analysis is typically an automated process that is integrated into the overall uncertainty analysis and calibration procedure. While setting up the SUFI-2 analysis, the specific parameters that should be included in the sensitivity analysis were defined as well as their ranges. Once the analysis was initiated, SUFI-2 automatically sampled the parameter space, runs the model for each parameter set, evaluated model outputs, and conducted the sensitivity analysis.

3.2.7 Model validation

The SWAT model requires validation which involves the comparison between the independent hydrological data and the calibrated model. This ensures that the model is reliable and capable of making future predictions of hydrological conditions. Similar to the calibration process there are different validation approaches such as temporal and spatial validation.

Temporal validation involves the comparison between the simulated model output and the observed data from a time period that differs from the calibration period. During this validation process the calibrated model generalises the different temporal conditions and consequently is not overfitting the specific calibration data (Arnold *et al.*, 2012b). It basically involves splitting the dataset into two sets and then calibrating the one set and validating the second set.

The spatial validation compared the simulated model output with spatially district observed data within the study area. This approach allows the model to extrapolate beyond the calibration location and test the model's spatial transferability. Research indicates that the ideal site for validation should have a range of land use characteristics and hydrological conditions which will ensure robust validation results.

In this study temporal validation was used since it aligns with the approach of dividing the time series data into three periods. It assesses the model's ability to generalise across different time periods,

ensuring that the calibrated model performs well under varying hydrological conditions. It provides insights into how well the model represents the temporal variability of hydrological processes, which is crucial for understanding watershed response to different climatic conditions and land use changes.

As part of the validation process various performance metrics are used to quantify the agreement between the observed data and the model output data. The most common metrics include Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS) statistics. All three performance evaluation criteria were applied during the validation process as it is crucial for achieving optimal model performance. These metrics provide quantitative measures of model performance, allowing researchers to assess the accuracy and reliability of model predictions.

3.2.8 Scenario analysis

After completing the validation phase and assessing the model's performance against observed data using established criteria such as NSE, R^2 , and PBIAS, the focus shifts to conducting scenario analysis. It involves exploring how the ArcSWAT model responds to various hypothetical conditions or management strategies.

After the model is fine-tuned and verified, it becomes a valuable tool for assessing how different management scenarios affect hydrological processes within the watershed. This can include mining practices, soil management and changes in land use. It can also be utilised to evaluate the effects of various scenarios on hydrological processes, as well as the evaluation of different mining practices, soil management strategies, and land use changes.

Scenario analysis allows stakeholders to explore alternative management options and make informed decisions to mitigate risks and optimise resource management strategies.

3.2.9 Documentation and reporting

The final step is to document the results of the ArcSWAT model, emphasising key findings and insights obtained from the temporal modelling and scenario analyses. Thereafter, compiling a comprehensive report detailing the methodology, data sources, model setup, temporal divisions, runoff modelling process, validation, calibration, and scenario analysis.

Effective reporting and communication facilitate knowledge sharing, stakeholder engagement, and informed decision-making, maximizing the impact of modelling efforts on water resources management and environmental conservation.

CHAPTER 4

DESCRIPTION OF STUDY AREA

4.1 Introduction

The study area is located in quaternary catchments B11C, B11D, and B11E that is situated in the Mpumalanga province, falling within the Olifants water management area (Figure 4-1). The study area covers an area of approximately 1 330 km² and the major urban area is Kriel, with Secunda and Bethal located just outside the study area (Figure 4-2). Information from pertinent hydrogeological databases, such as the Groundwater Resource Directed Measures, was acquired from the Department of Water and Sanitation (DWS). Table 4-1 displays the parameters for the quaternary catchments located within the identified study area boundaries.

The study area is situated in the headwaters of the Steenkoolspruit, Trichardspruit, Rietspruit, Blesbokspruit, Krapfontainspruit, Pieketspruit and Debeerspruit catchment areas (Figure 4-2). Geographically, the area spans from 28° 57' E – 29° 27' E to 26° 07' S – 26° 31' S. The primary river in this region is Steenkoolspruit, which serves as the largest tributary of the Olifants River, flowing northward.

Table 4-1 Summarised quaternary catchment information

Quaternary catchments	Total area (km ²)	Recharge (MAR)* (mm/a)	Rainfall (MAP)* (mm/a)	Evaporation (MAE)* (mm/a)	Average groundwater level (mbgl)
B11C	385.4	33.2	672.7	1,550	8.4
B11D	550.9	30.1	671.5	1,600	8.9
B11E	466.7	32.2	682.4	1,600	8.6

* MAR = mean annual recharge; MAP = mean annual precipitation; MAE = mean annual evaporation
Source: Department of Water and Sanitation (2013)

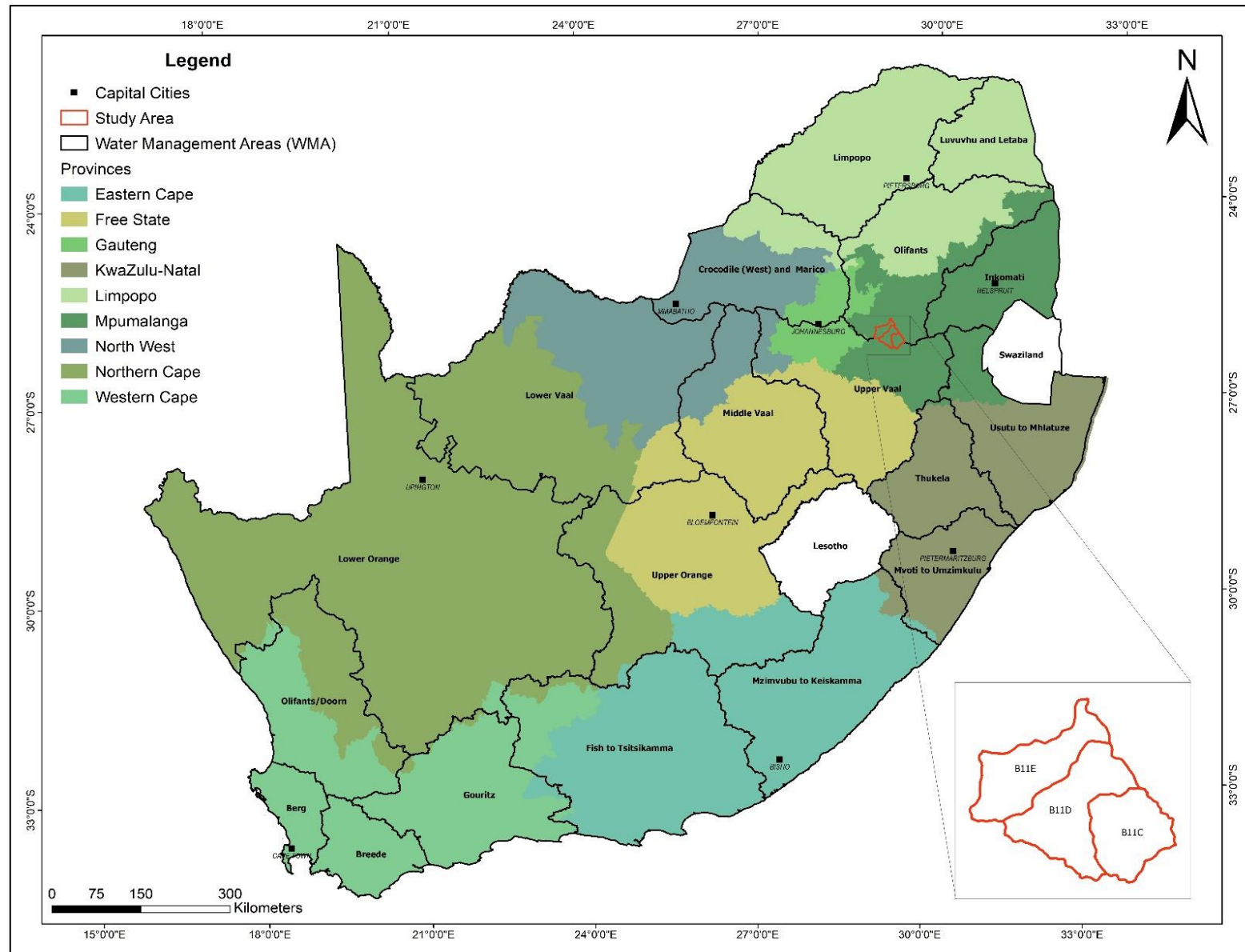


Figure 4-1 Locality map of the study area, showing the provinces, water management areas and capital cities (Author's own, 2024)

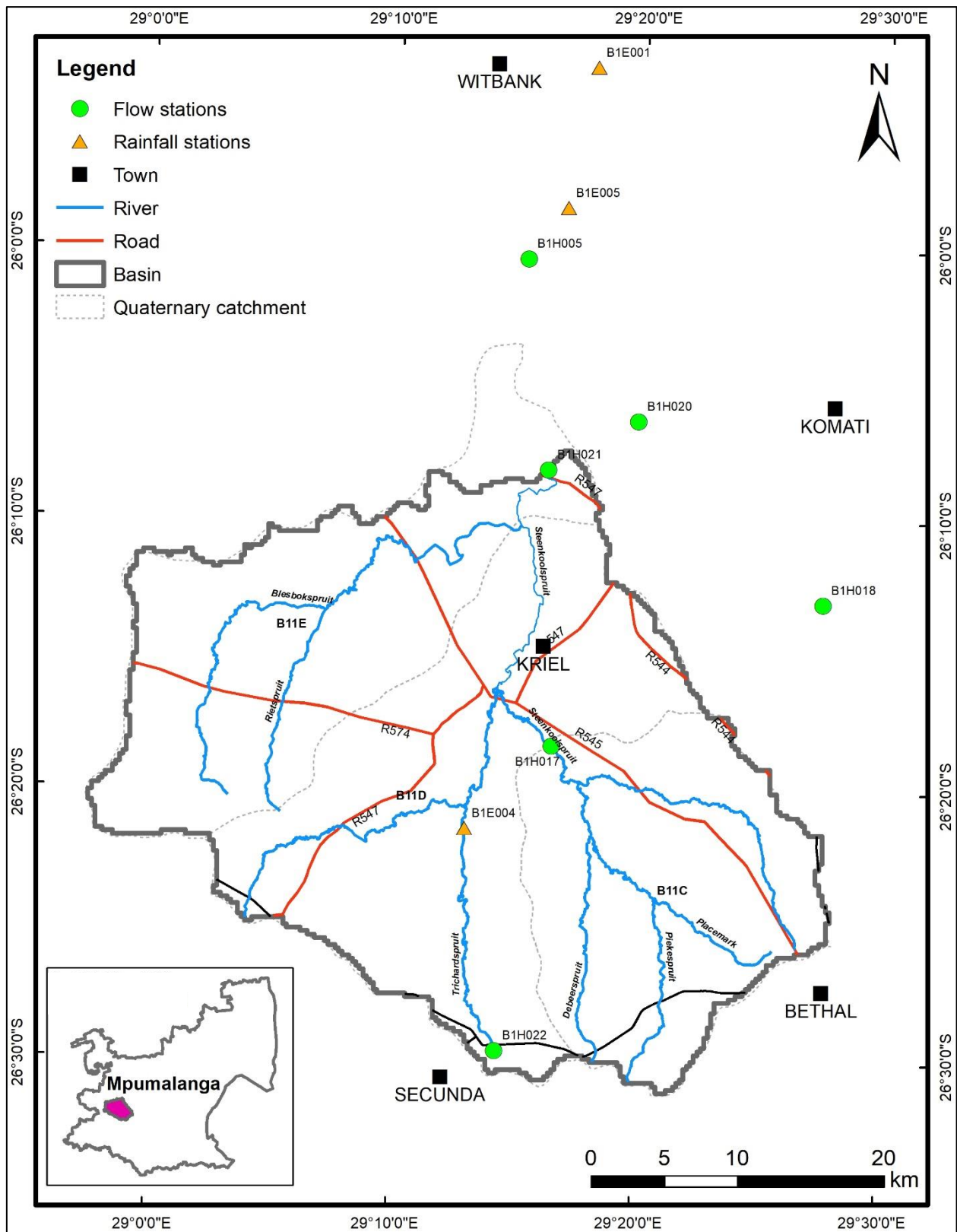


Figure 4-2 Location of study area relative to the Mpumalanga province, showing main rivers, roads, towns, flow stations and rainfall stations (Author's own, 2024)

4.2 Drainage and topography

The study area included three quaternary catchments (B11C–B11E), with most, but not all, of quaternary catchment B11E as part of the study area. To guarantee the exclusive use of the designated study area for modelling purposes, the boundary was delineated using ArcGIS™. The delineation was done from the stream gauge B1H021, at the outflow of Steenkoolspruit in the north of the study area (Figure 4-2). The generated DEM was used as a boundary to extract the necessary information of the study area and was later used in the ArcSWAT model to delineate the sub-catchments (Figure 4-3).

The topography of the study area represents the arrangement of land surface, which includes its relief and the location of its man-made and natural features. Its altitude varies, ranging from approximately 1 698.32 mamsl upstream to 1 519.86 mamsl downstream. The topographic map shows the areas of different elevations in the study area. For example, in the study area the steepest area is the south-eastern to south-western sections from where it gradually decreases towards the northern region of the study area. The drainage in the study area flows northward via Steenkoolspruit, where it eventually joins the Olifants River in the northern region before contributing to the Limpopo River (Rafundisani, 2018). In addition to stream flow and surface water, the topography of the research area also plays a crucial role in shaping the course of groundwater flow. This, in turn, exerts an impact on both the recharge and discharge of groundwater.

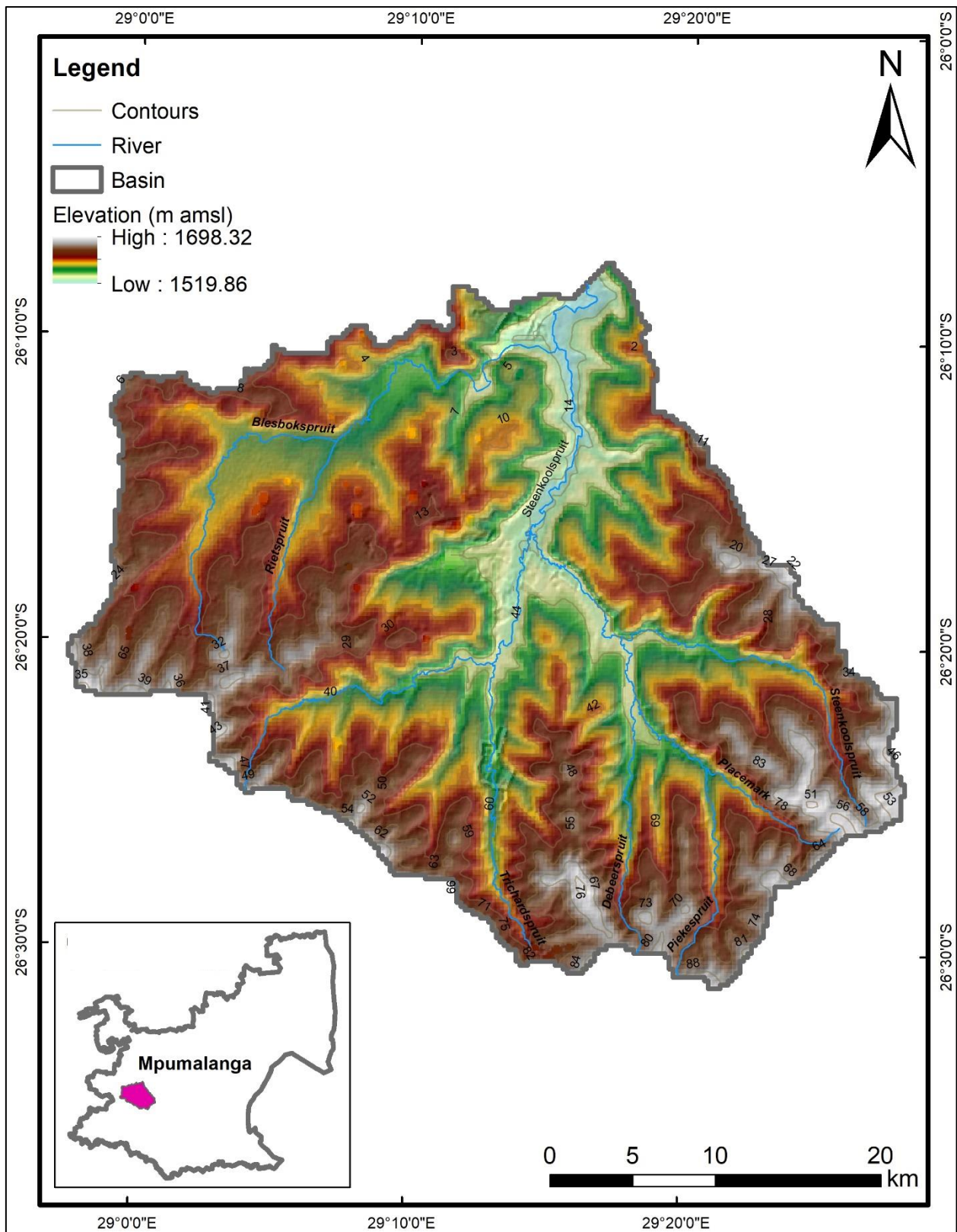


Figure 4-3 Topography and drainage of study area (Author's own, 2024)

4.3 Data sources

Prior to initiating the data gathering process, it was important to clearly outline the study area so that only the appropriate data would be obtained (Table 4-2). This preliminary step aimed at improving the efficiency of the process of collecting data and thereby enhancing the overall quality of the input data.

Table 4-2 Data sources with relevant scale used for study area

Name	Source	Scale	Purpose
Digital elevation model	Shuttle Radar Topography Mission 90-meter digital elevation model (SRTM90) United States Geological Survey https://earthexplorer.usgs.gov/	1:50 000	Employ for the delineation of the area under investigation; the catchment delineation; and the backdrop for the maps
Geology	Council for Geoscience (CGS)	1:250 000	To map the geological features in the study area
Soil	The Food and Agriculture Organization (FAO) https://data.apps.fao.org/map/catalog/signout	1:250 000	Hydrological soil groups of the study area used as input for the ArcSWAT model
Land cover 1990 & 2009	Digital Earth Africa (DEA) Open Data Cube https://www.digitalearthafrika.org/	1:75 000	Illustrates the utilisation of land in the designated study area, serving as input for the ArcSWAT model
Rainfall data	Department of Water and Sanitation (DWS) https://www.dws.gov.za/Hydrology/	1:50 000	Provides the rainfall data for B1E005 rain gauge and is used as input for the ArcSWAT model
Flow data	Department of Water and Sanitation (DWS) https://www.dws.gov.za/Hydrology/	1:50 000	Provides the stream flow data for the B1H021 stream gauge and is used for calibration during modelling process
Vegetation data	South African National Biodiversity Institute (SANBI)	1:250 000	To map types of vegetation present in the study area
Hydrological features such as rivers and dams	Middleton, B.J. & Bailey, A.K. 2011. <i>Water resources of South Africa, 2-0-05 Study (WR2005). User's guide, Version 2.</i>	1:50 000	Indicates the water management area, quaternary catchments, dams, rivers and several other hydrological features used in the mapping

4.4 Physical characteristics

4.4.1 Physiography

The physical features and characteristics of landscapes play a pivotal role in understanding the geological, climatic, and ecological dynamics of a particular region. This study delved into the intricate physiography of the study area, seeking to unravel the climate, landforms, and natural processes that have shaped its unique terrain. Through a comprehensive examination of the topography of the area, its land use and environmental features, the study aimed at contributing valuable insights that would not only enhance our scientific understanding but would also have practical implications for sustainable land management and resource conservation.

4.4.1.1 Climate

Utilising the climate conditions of the town of Kriel as the basis for the study area was chosen due to its role as the primary town within the research region.

Kriel has a highland tropical climate which is characterised by long warm, and partly cloudy summers, with short, cold, dry, and clear sky winters. During the course of the year, the temperature generally fluctuates between 0 °C and 25 °C, seldom dropping below –2 °C or exceeding 29 °C (Weatherbase, 2016). The warm season spans over six months, from about the end of September to the end of March, with an average high daily temperature exceeding 23 °C. January is the warmest month of the year, with an average high of 25 °C and a low of 14 °C (Weatherbase, 2016). Conversely, the chilly period spans around two months, starting in early June and concluding at the end of July, during which the average daily high falls below 19 °C. The coldest month of the year is July, featuring an average low of 1 °C and a high of 18 °C (Weatherbase, 2016). Figure 4-4 shows the long-term monthly average temperature for Kriel recorded over a 112-year period.

The likelihood of wet days in Kriel varies significantly throughout the year. The wet season continues for about five and a half months, from the middle of October to the end of March, with a probability exceeding 27% chance of any given day being wet (Weatherbase, 2016). December has the highest number of wet days in Kriel. Conversely, the dry season lasts for about six and a half months, from the end of March to the middle of October, and July is the month with the fewest wet days. The long-term average rainfall for Kriel is shown in Figure 4-5 over a period of 112 years.

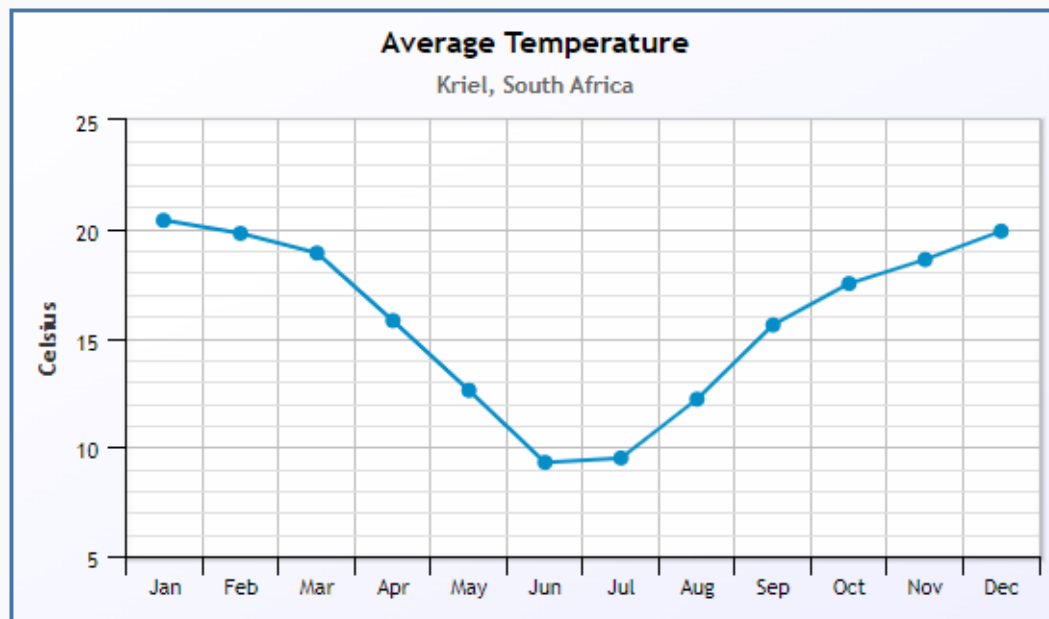


Figure 4-4 Long-term monthly average temperature for Kriel, South Africa (Weatherbase, 2016)

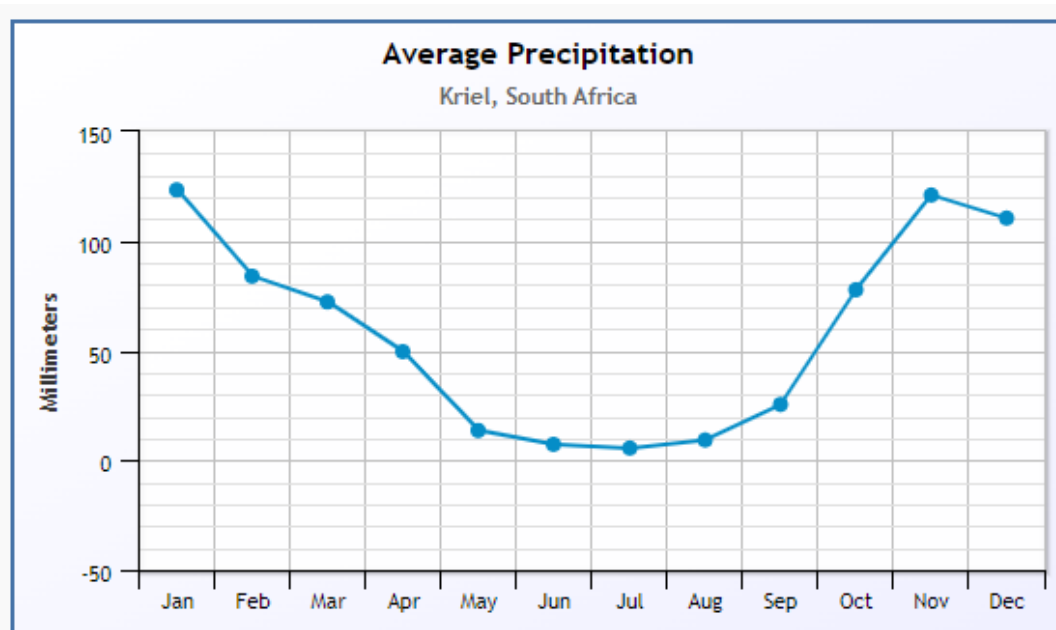


Figure 4-5 Long-term monthly average rainfall for Kriel, South Africa (Weatherbase, 2016)

4.4.1.2 Vegetation

Vegetation type is dependent on the climatic conditions of the catchment area as well as the mean annual rainfall. The vegetation in both the Eastern Highveld grassland and Soweto Highveld grassland is characterised by a grassland ecosystem adapted to the semi-arid conditions of the Highveld (high lying) region of South Africa (Figure 4-6). While there may be some variations based on specific local factors, the general vegetation types are similar.

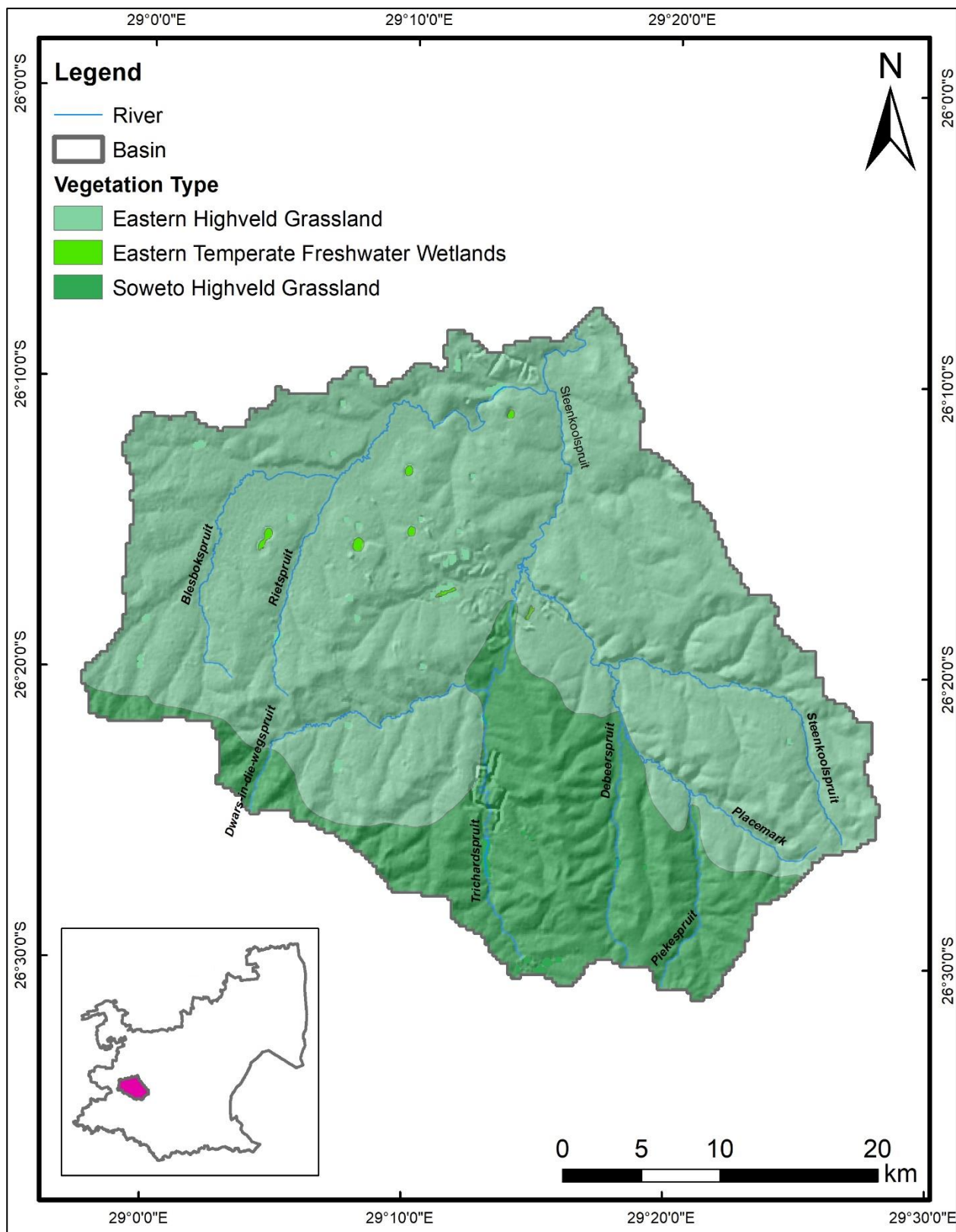


Figure 4-6 Vegetation of study area (Author's own, 2024)

4.4.1.3 Soils

The soil data used in the study were obtained from the FAO (year), chosen for its compatibility with soil codes that could seamlessly integrate into the SWAT database. The classification of these soils is aligned with the hydrological groups specified in the FAO table, establishing a correlation with the classification system of the Soil Conservation Services (SCS) tailored for South Africa.

The SCS for South Africa makes use of hydrologic soil property information for the approximation of surface runoff from a catchment (Macfarlane & Bredin, 2017). According to the geological survey by the United States Department of Agriculture and the Natural Resources Conservation Service (USDA & NRCS, 2007), the classification of soils can be conducted using hydrologic soil groups. These groups are built on the measured rainfall, runoff, and infiltrometer data. The groupings are furthermore built on the assumption that soils located in climatic regions with similar texture, structure, extent of swelling, water table, and transmission rates of water, have runoff responses that are similar (USDA & NRCS, 2007).

Specifically, the FAO soil type *sandy clay-loam* (Lc64–2b–722) corresponds to Group C soils according to the SCS classification. Similarly, the FAO soil type *clay* (Vc1–3a–954) is indicative of Group D SCS soils (Figure 4-7). According to the USDA and NRCS (2007), the Group D soils are the primary soil group in the study area occupying most of the study area, specifically in the east, south, west, and central parts. This soil series is a group of soils that can generally be characterised as clay soils that swell significantly when wet, and typically have a limited ability to transmit water, making them more prone to runoff and erosion. These soils may have challenges related to water drainage and can be less suitable for certain land use, particularly if no erosion control measures are implemented.

The Group C soils occupy a small section in the northern part of the study area and can generally be characterised as having a moderate ability to transmit water and are often characterised by a mixture of textures, such as clay loams or shallow sandy loam soils. These soils are generally considered to have a moderate risk of erosion and are suitable for a range of land uses, including agriculture.

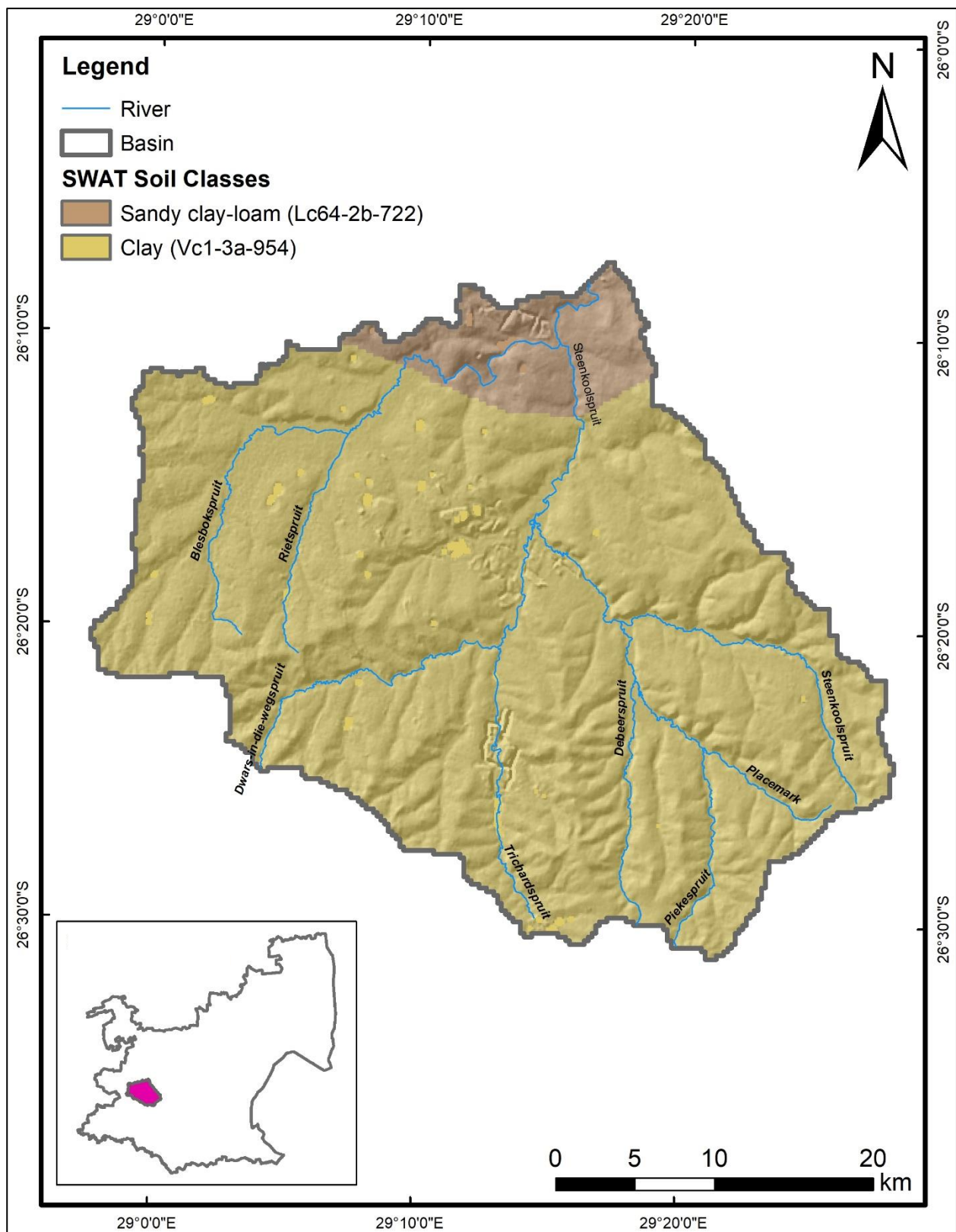


Figure 4-7 Soil classes of study area (Author's own, 2024)

4.4.1.4 Geology

The largest part of the study area is underlain by the Permian aged Vryheid Formation of the Ecca Group of the Karoo Sequence. In the southern section of the study area, a smaller area is underlain by the Jurassic aged Karoo Dolerite. Additionally, there are minor intrusions of the Mokolian aged Lebowa Granite Suite associated with the Bushveld Complex. The study area also features the Vaalian aged Selons River Formation of the Rooiberg Group of the Transvaal Sequence.

According to the 1:250 000 Geological Map Sheet (2628 East Rand) the Vryheid Formation is the oldest formation among all the formations in the study area (Figure 4-8). The formation consists of light grey sediments, ranging from fine to coarse sandstone to siltstone. The presence of dark coloured siltstones is due to the carbon enrichments and the development of coal beds (Butler, 2019). Sandstones, deltaic mud rocks, sporadic coal seams, as well as deposits from coastal and fluvial environments can also be identified in the formation. These deposits likely gathered along a sandy shoreline that extended past vast swampy areas. Within these swamps, plant material accrued over time, forming the coal deposits that are currently mined (Johnson *et al.*, 2006). Notably, the Vryheid Formation is known for its significant coal reserves, with a substantial amount of coal economically extracted in South Africa occurring in this formation.

The Lebowa Granite Suite is younger than the Vryheid Formation, belonging to the Bushveld Complex. The Complex is renowned for its significant concentrations of magnetic ores, along with numerous pegmatitic and hydrothermal deposits (Cairncross & Dixon, 1995). Additionally, it features industrial mineral deposits that originated through the metamorphism of the underlying rocks in the Complex. The Lebowa Granite Suite is one of the main lithologies of the Bushveld Complex. This Suite consists of granite with a medium-grained porphyritic texture, exhibiting a red hue, and characterised by coarse-grained biotite granite (2628 East Rand). The Selons River Formation, dating back to the Vaalian Age, is younger than both the Vryheid Formation and the Lebowa Granite Suite. At its base, the Selons River Formation exhibits either quartzite or sandstone, mainly consisting of red rhyolite (Fourie, 2021).

The early Jurassic Age sheet-like Karoo dolerite intrusions are the youngest of the four formations in the study area. The dolerites exhibit a significant array of intrusive dolerite dykes and sills, which, according to Svensen *et al.* (2012), swiftly penetrated around 183 million years ago. This intrusion later contributed to the formation of the Drakensberg lavas that overlay the Karoo dolerites (Cox, 1992; Duncan *et al.*, 1997). The dolerites consist of basaltic andesite, characterised by enriched trace elements and sub-alkaline tholeiitic basalts. The study area distinctly features ongoing coal developments within the Karoo sequence, and the extraction of coal from these seams has played a vital role in the establishment and growth of eMalahleni City and the adjacent settlements.

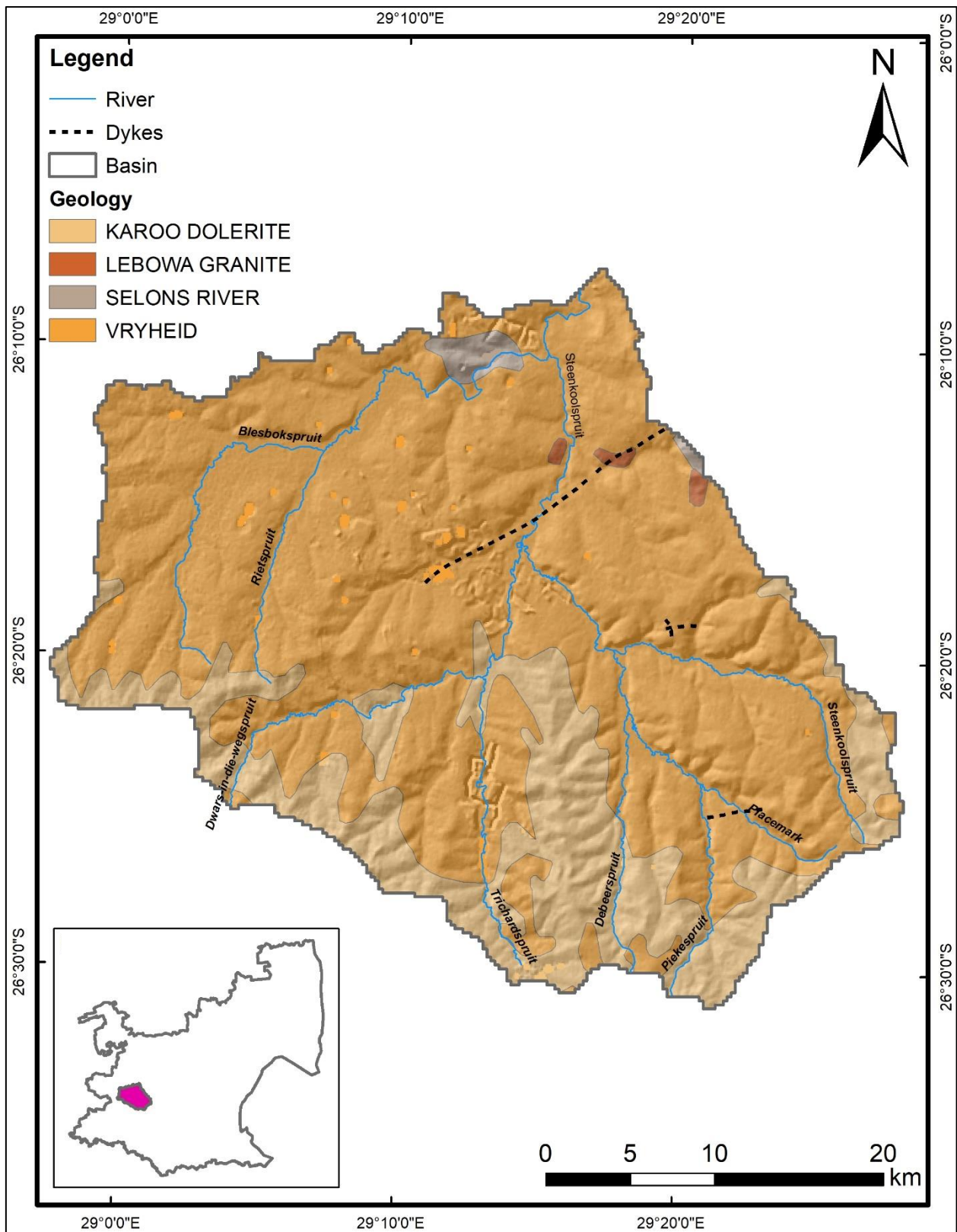


Figure 4-8 *Geology of study area* (Author's own, 2024)

4.5 Meteorological data

The DWS is the primary institution responsible for rainfall and flow data. Since the 1970s, there has been a substantial decline in available rainfall datasets (De Klerk, 2018), posing challenges in obtaining relevant rainfall and flow data for specific time periods. This limitation has inherently narrowed the sample area, because additionally to this it is crucial that the temporal aspects of the rainfall and flow data correlate in terms of time series data (see Figure 4-9).

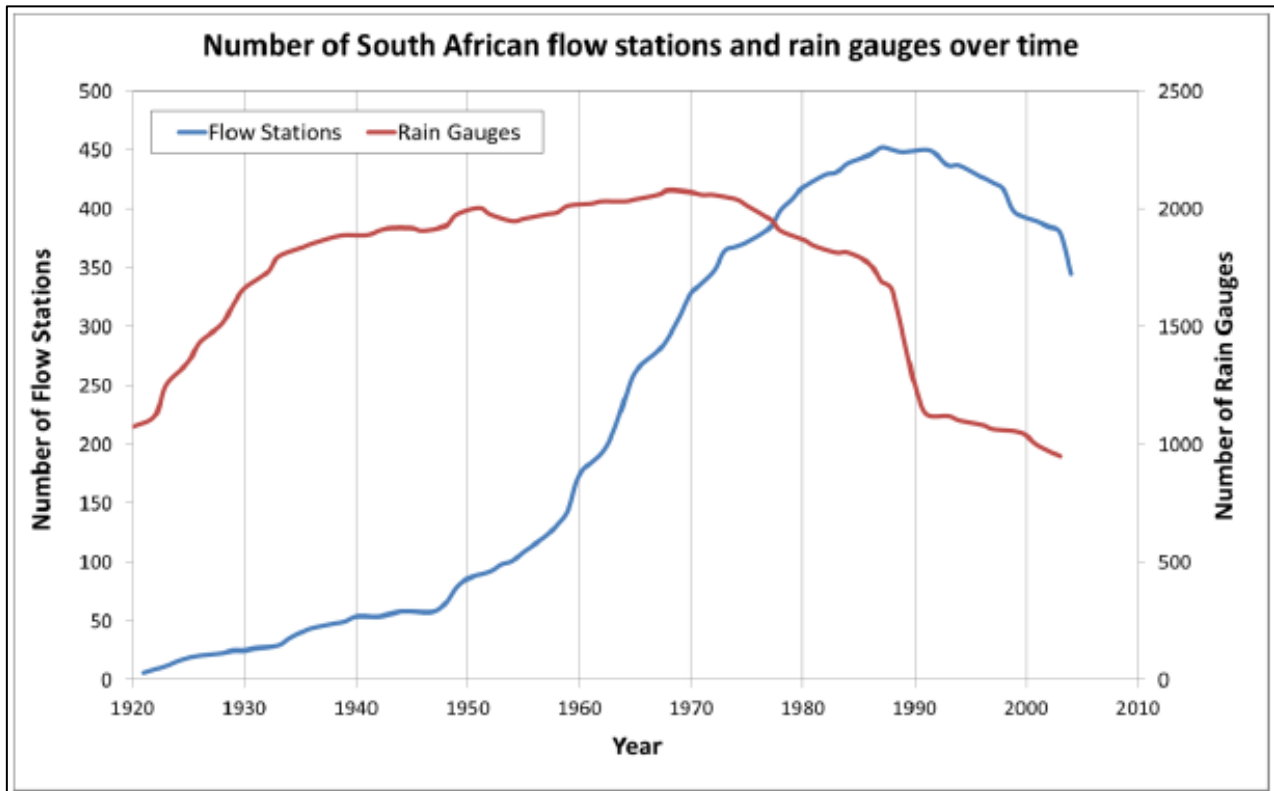


Figure 4-9 *Rainfall gauges and flow stations with available datasets per year* (Pitman, 2011)

4.5.1 Rainfall

While numerous rainfall gauges exist in and around the study area, most of them are either non-functional or have gaps in data coverage, ranging from a few days to sometimes months of missing data, and consequently causing discontinuous data. From the DWS database there are three rainfall gauges (B1E001, B1E004 and B1E005) with available data located in and around the study area. Table 4-3 indicates the rainfall gauges with their available monthly rainfall data period.

Table 4-3 DWS rain gauges with available rainfall data

Rainfall gauge	Months of available data (total)
B1E001	1964-02-07 – 1991-06-30 (341) 1991-08-01 – 1993-03-31 (32) 1993-05-01 – 1993-05-30 (1) 1993-09-01 – 2005-11-30 (159) 2006-01-01 – 2009-04-01 (52)
B1E004	1980-11-30 – 1982-07-30 (33) 1982-09-01 – 1984-02-29 (30) 1984-05-01 – 2002-04-30 (228) 2002-06-01 – 2003-11-01 (30)
B1E005	1986-12-03 – 1993-02-01 (87)

4.5.2 Flow

Similar to the rainfall gauges, the study area is also equipped with several flow stations, occasionally experiencing gaps in data coverage. Specifically, six flow stations (B1H005, B1H017, B1H018, B1H020, B1H021 and B1H022) were identified in or in proximity to the study area. Table 4-4 indicates the flow stations with their available monthly flow data period.

Table 4-4 DWS flow stations with available flow data

Date	Months
B1H005	1972-07-13 – 1981-10-30 (111) 1982-04-01 – 1982-10-30 (35) 1983-02-29 – 1990-11-30 (110) 1991-05-01 – 2005-07-31 (170) 2005-11-01 – 2018-10-30 (155) 2019-02-01 – 2019-10-30 (37)
B1H017	1989-12-01 – 1995-11-30 (71) 1996-06-01 – 2019-06-30 (277)
B1H018	1989-12-01 – 1997-04-30 (89) 1997-07-01 – 2020-01-31 (265) 2020-04-01 – 2022-04-30 (25)
B1H020	1990-04-01 – 1992-02-29 (22) 1992-06-01 – 1995-11-30 (41) 1996-03-01 – 2003-03-31 (85)
B1H021	1990-11-01 – 2012-10-30 (263) 2013-01-01 – 2022-05-31 (113)
B1H022	1991-04-01 – 1992-03-31 (12) 1992-05-01 – 1996-11-30 (54) 1997-01-01 – 2001-11-30 (58) 2022-01-01 – 2022-04-30 (4)

4.6 Anthropogenic factors

4.6.1 Land cover

According to Rabie (1996:330), to effectively manage water resources, one should always keep in mind that the conditions, aquatic life, and water quality of any water body are easily influenced by events happening within the catchment. There are various anthropogenic activities that impact the water resources within the study area. Among these, key contributors include industrial operations such as mining, agricultural practices, and coal reserves designated for power stations. Additionally, there are lesser contributors such as manufacturing and the presence of informal settlements.

Because of the restricted availability of data, this research utilised land cover data from 1990 to depict the average conditions during the reference period, while data from 2009 was employed to illustrate the recent period. Land use in the basin of the study area experienced alterations during these two time spans, as indicated in Table 4-5. From the 1990 and 2009 land cover dataset for the study area (Figure 4-10 and Figure 4-11), the major land covers are cultivation, woodlands and grasslands (i.e., natural areas), along with mining and wetlands. The natural areas predominantly consist of grasslands utilised for grazing, making cultivation the predominant land use activity in the study area. Mining activities are likely to alter the infiltration and runoff characteristics of the study area basin in their immediate area.

Table 4-5 Land cover statistics for the study area

Land cover classes	1990		2009	
	Area (km ²)	Percentage of coverage (%)	Area (km ²)	Percentage of coverage (%)
Water	7.45	0.57	8.27	0.62
Wetlands	86.48	6.50	70.47	5.30
Woodlands and grasslands	519.82	39.08	582.95	43.83
Low shrub lands	10.96	0.82	3.98	0.30
Cultivated fields	645.77	48.55	537.40	40.41
Plantations	4.61	0.35	5.82	0.44
Mines	39.72	2.99	101.85	7.66
Bare non-vegetated	2.01	0.15	6.63	0.50
Urban	13.09	0.98	12.63	0.95
Total	1 330	100	1 330	100

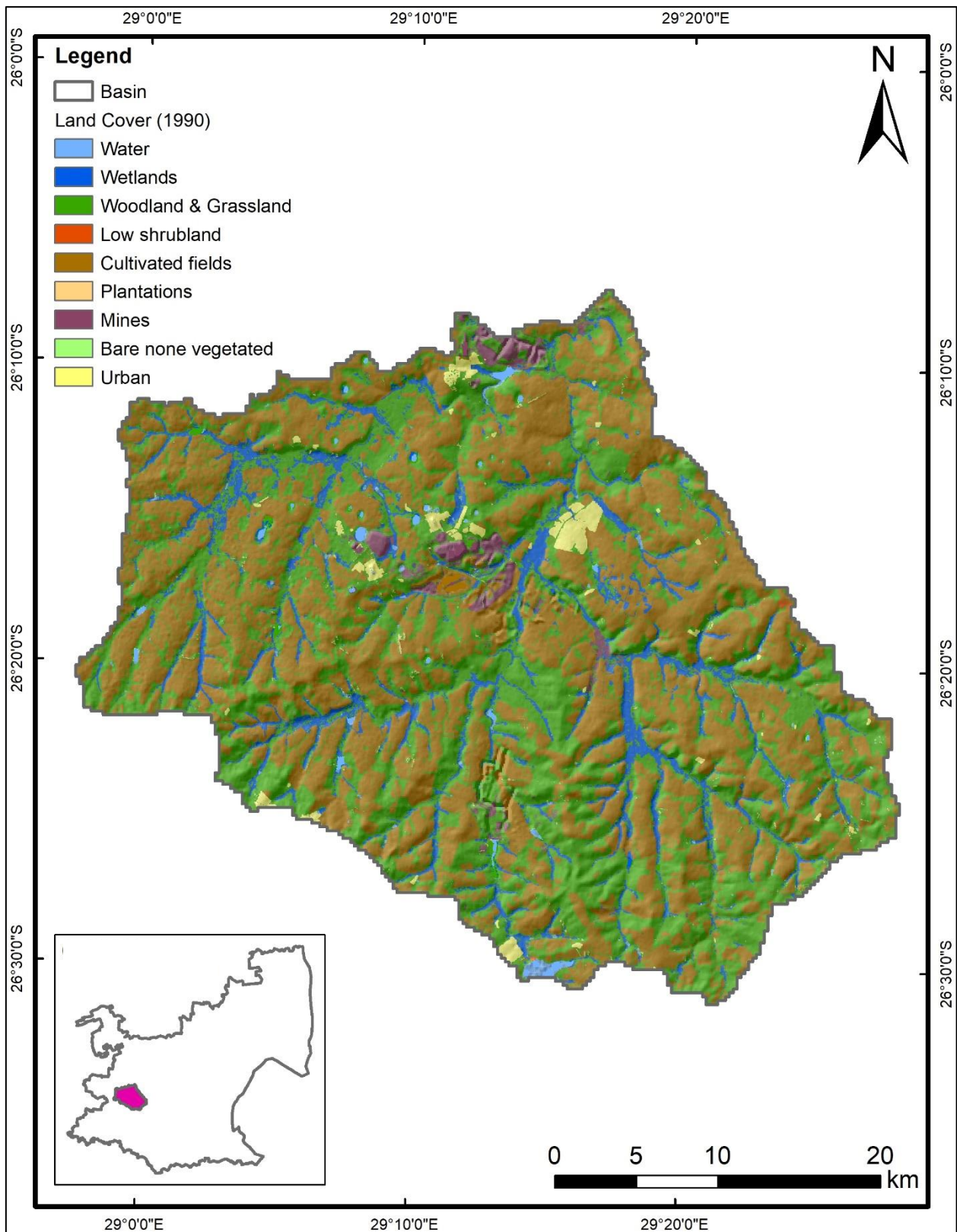


Figure 4-10 Land cover in the study area in 1990 (Author's own, 2024)

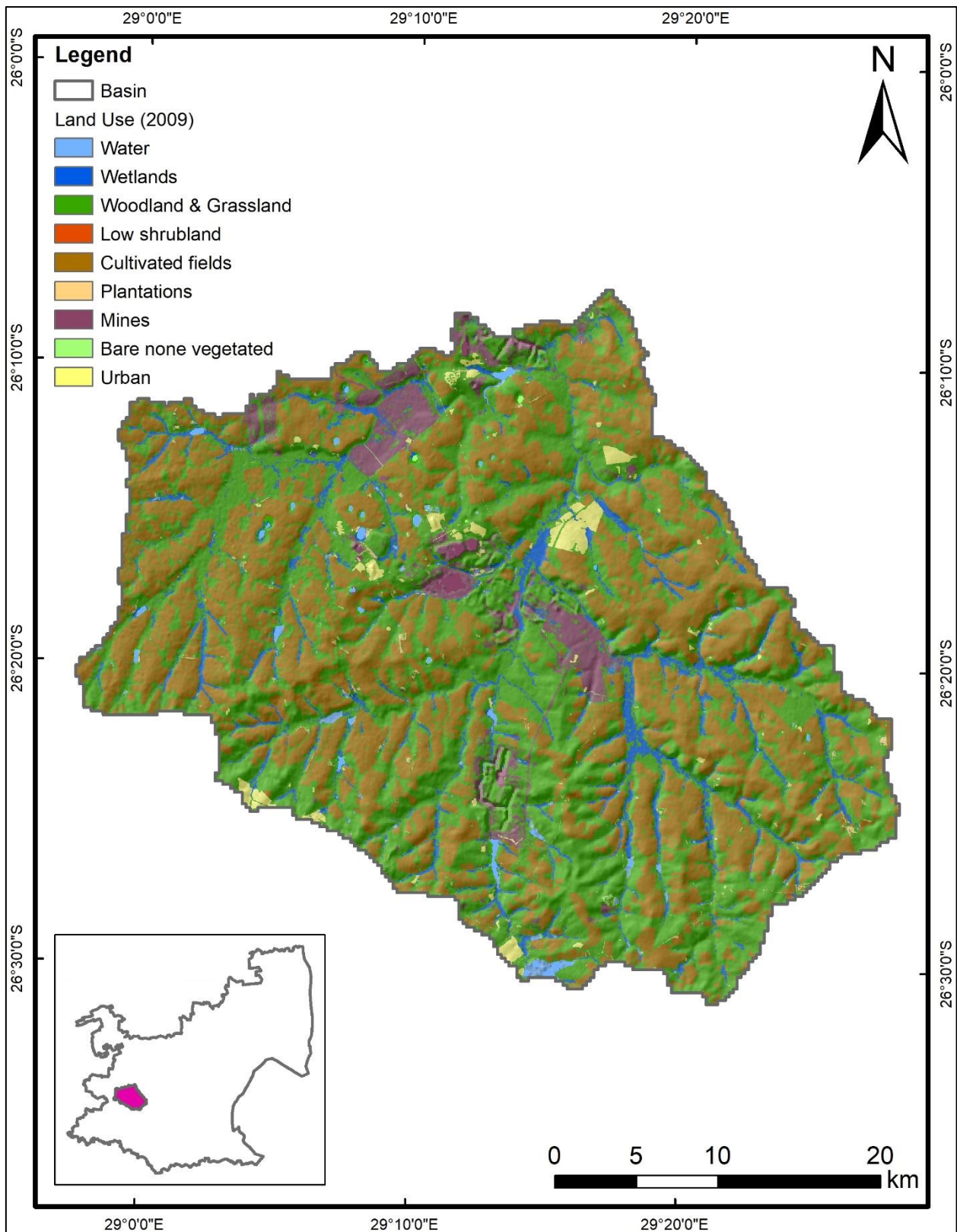


Figure 4-11 Land cover in the study area in 2009 (Author's own, 2024)

4.6.2 Mining

The study area consists of an approximate area of 1 330 km², and a significant segment has been influenced by mining. Within this area, mining operations have been established, ranging from 2.99% in 1990 to 7.66% in 2009 (see Table 4-5), each having different economic lifespans and varying impacts of both groundwater and surface water resources. Additionally, numerous substations exist within the study area, including the Kriel Power Station, recognised as one of the biggest power plants using coal in the southern hemisphere (Figure 4-12).

4.6.2.1 Background

Coal mining in South Africa has historical roots dating back to the late 19th century, reflecting the timeline of gold mining in the Witwatersrand region. Initially linked closely to nascent gold mines, coal extraction rose as South Africa envisioned its industrial future. Despite current concerns about the environmental impact of coal amid climate change, it remains a predominant global primary fuel, constituting over a third of the world's total fuel consumption for electricity generation (Mann & Carr, 2023).

The study area is situated within South Africa's coal belt, an area housing over 100 coal mines and numerous coal-fired plants that define its industrial landscape. Mpumalanga, where the study area is located, contributes approximately 80% of the nation's coal supply. In South Africa, about 40% of coal is allocated for power production, meeting around 77% of the country's energy requirements (Mann & Carr, 2023).

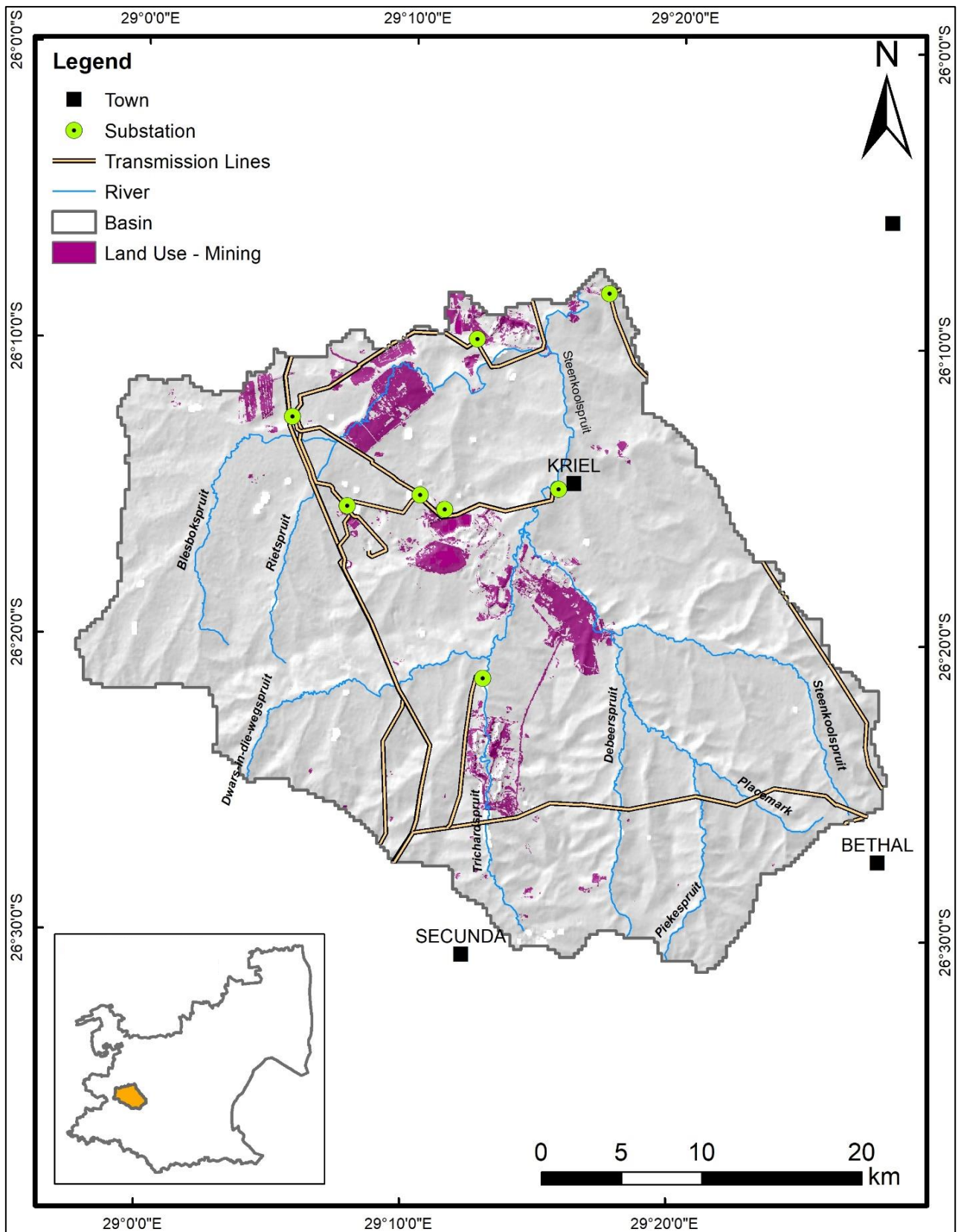


Figure 4-12 Mining and other infrastructure in the study area (Author's own, 2024)

An example that highlights the mining sector is the allocation of the coal supply contract in 1969 to the Coal Division of the Anglo-American Corporation for the construction of a new 3 000 MW power station at Kriel. Situated in the eastern Transvaal between Ogies and Bethal, the Kriel Division adapted its plans, combining underground and opencast mining to enhance volumetric extraction, ultimately producing 4.1 million tons underground and 4.5 million tons from opencast operations (Buchan *et al.*, 1980).

The escalating demand for coal, driven by the global need for electricity, propels rapid expansion of coal mining across the Highveld grasslands. The expansion puts increased pressure on the biodiversity of grasslands, including wetlands and water production. As demand increases, managing the impact of mining on the grassland biome becomes a biodiversity challenge. Incorporating spatial biodiversity information into mining decisions is a proactive step. Biodiversity management possibilities also exist within the regulatory and market forces shaping coal mining practices. Opencast mining poses severe threats to biodiversity, as it effectively erases natural values from the landscape, including detrimental effects on wetlands. Notably, rehabilitated opencast pits often exhibit decanting issues, highlighting the need for sustainable practices in the face of expanding coal mining activities (Banks *et al.*, 2011).

The changes in water quality are considered to be mostly affected by the consequences of mining operations. This is due to multiple unwanted contaminants that are disposed into the ground and surface water due to mining operations (Kalule-Sabiti & Heath, 2008). Most mines require a significant volume of water for production and as a result from mining contaminated products are disposed into the wastewater. The water that has been utilised is subsequently released as effluents into adjacent water sources. Mining waste sources such as waste rock, slimes or overburden all have adverse effects on the aquatic environment. Therefore, a conclusion can be made that the mining operations in and around the town of Kriel places an enormous amount of pressure on the water resources in the Mpumalanga province (North West Province State of the Environment Report, 2002).

4.6.3 Agriculture

The Mpumalanga Highveld, in contrast to the Mpumalanga Lowveld, stands out as an excellent agricultural area due to its grassland nature. The grassland contributes to the development of highly fertile soil, nurtured by the fertile grassroots. Furthermore, the region's agricultural potential is sustained by above-average rainfall compared to the South African average and unique geological formations, specifically sandstone layers that also contain coal deposits. These sandstones create a perched water table, ensuring water retention close to the surface, benefitting both agricultural and natural vegetation. This unique combination makes the Mpumalanga Highveld a valuable resource for food production. Notably, it consistently yields maize, even during drought years when other

maize-producing areas face challenges. Maize, a staple crop, thrives in this region, emphasising its significance in ensuring food security (Chiumia, 2021).

4.6.3.1 *Impact of mining on agriculture*

For various reasons, the coal mining and agricultural industries find themselves uneasy neighbours. Foremost, among these concerns is the stark reality of climate change, with the burning of coal standing as a major contributor. The tangible effects of climate change, including extreme weather events, are already evident. Also, these industries are committed to a global temperature increase of at least 2°C, with South Africa facing even more pronounced changes. Experts warn that such a scenario is unsustainable, predicting consequences such as droughts, floods, the movement of climate refugees, and the potential collapse of economic and political systems (Munnik, 2016).

Another critical issue is the contamination of water resulting from coal mining activities. While mines only utilise slightly less than 5% of the water in the upper Olifants catchment area, they are responsible for almost 80% of the water's sulphate load. This sulphate serves as an indicator of, and plays an active role in, the occurrence of acid mine drainage. With its acidic properties, mobilisation of heavy metals, and the tendency to induce salinity, acid mine drainage greatly impacts agriculture (Munnik, 2016).

A third concern revolves around the destruction of soil caused by coal mines. Open pit mining involves the blasting of sandstone and plinthite (clay) layers that support the water table in the Mpumalanga Highveld, a vital component for the fertility of grassland soils. Unfortunately, once these layers are disrupted, restoration becomes a nearly impossible challenge. Even if a concrete layer or clay is built, it proves incapable of withstanding the settling in of the 'overburden' that fills the pits, a process that exceeds the mine's profits in expense (Bruwer & Khwidzhili, 2022).

The coexistence of coal mining and agriculture in certain locations is particularly noteworthy due to the separation of mineral rights from surface rights. This distinct separation allows mining and agricultural activities to share the same geographical areas. While this coexistence raises critical environmental concerns, including the impact on water quality, soil integrity, and climate change, it plays a significant role in shaping the region's energy landscape. The intricate relationship between coal mining practices and the electricity generation sector in a region dominated by coal-fired power stations is thus influenced by the dynamic interaction between these industries. Understanding these environmental challenges becomes crucial in evaluating the broader implications for electricity generation and sets the stage for further exploration in the following section.

4.6.4 Electricity and urban development

The economic landscape around Kriel is largely centred around agriculture and mining, although the generation of electricity also plays a pivotal role.

4.6.4.1 History of the Kriel Power Station

The historical trajectory of power stations in South Africa is marked by a diverse mix of electricity sources. The journey began in 1886 when gas engines and steam turbines illuminated the streets of South African cities (Banks *et al.*, 2011). Subsequently, hydroelectric power found its place in the electricity mix. However, it was not until 1912 that discussions about the first coal power station emerged, primarily driven by the necessity to power the national railway line (Banks *et al.*, 2011). This marked the initiation of a broader commissioning process for coal-powered stations.

The conceptualisation and development of Kriel Power Station commenced in the early 1960s, with construction launching in 1970. By December 1979, the station reached full operational capacity, becoming the most extensive power station fuelled by coal in the Southern Hemisphere at the time (Banks *et al.*, 2011). This ground-breaking achievement set the stage for subsequent colossal power station facilities such as Matla, Duvha, Kendal, Lethabo and Matimba, along with Kriel Power Station was also a forerunner. Being one of the pioneering stations to receive coal from a completely automated coal mine, the fuel seamlessly reached the boilers without any human involvement.

4.6.4.2 Power stations at present

Presently, Kriel Power Station stands as a robust contributor to South Africa's electricity grid, generating 3 000 MW from its six units. Each unit is designed with a rated capacity of approximately 500 MW, allowing the station, at full capacity, to contribute a substantial 6.5% to the national electricity grid. According to the Department of Mineral Resources (cited by Banks *et al.*, 2011) the demand for coal, particularly from the electricity sector, remains predominant, addressing approximately 77% of the nation's primary energy demands and fulfilling 90% of its electricity generation necessities.

Eskom, the state-owned utility, plays a pivotal role, generating around 95% of South Africa's electricity, with approximately 90% originating from coal-fired power stations (Banks *et al.*, 2011). However, the use of low-grade coal in these power stations comes with environmental considerations, as it results in increased release of gaseous and particulate emissions. Extensive reserves of coal and significant ash production also contribute to fugitive particulate matter (Banks *et al.*, 2011).

South Africa's coal industry plays a central role, with more than 90% of generated electricity originating from coal-fired power stations. Major mining groups, including BHP Billiton Energy Coal South Africa, Anglo Coal, Sasol, Exxaro Resources, and Xstrata, control nearly 90% of the saleable coal production (Banks *et al.*, 2011). According to the World Coal Institute (cited by Banks *et al.*, 2011) the global demand for South African coal, primarily driven by European nations, underscores the country's position as a significant coal exporter.

As the demand for electricity continues to surge, coal mining expands across the Highveld grasslands, intensifying pressure on biodiversity, wetlands, and water production. Despite increased electrification of households, coal remains a prevalent heating energy source, particularly due to associated electricity costs (Department of Environmental Affairs, 2012).

4.7 Conceptual site model

Having established a detailed description of the study area in the preceding sections, the focus now shifts towards the development of a conceptual site model (CSM). The CSM serves as a fundamental tool for understanding the complex hydrological processes within the catchment. By synthesizing the geographical, hydrological, and environmental characteristics outlined earlier, the CSM provides a holistic framework to conceptualise the movement and distribution of water within the study area.

Figure 4-13 illustrates the CSM from south (up-gradient) to north (down-gradient) across the site. It outlines the existing land use patterns and infrastructure within the study area. This includes mining, agricultural areas, residential, and commercial areas. Understanding the distribution and density of land use helps identify potential sources of contamination, vulnerabilities, and areas of concern. Key hydrological features are highlighted in the CSM to assess their impact on environmental processes and hazards. This may include surface water bodies, such as dams and rivers, along with groundwater aquifers.

Finally, the CSM integrates the hydrological cycle which is crucial for understanding how water moves through the study area. The hydrological cycle delineates the movement of water through various interconnected processes, encompassing precipitation, infiltration, surface runoff, groundwater flow, evaporation, and water storage. Precipitation patterns, influenced by natural and anthropogenic factors, dictate the distribution of water inputs across the catchment. Infiltration and soil moisture dynamics govern the partitioning of rainfall into runoff and groundwater recharge, influenced by soil characteristics and land use practices. Surface runoff pathways, including overland flow and channelized flow, shape the hydrological response of the landscape, directing water towards streams, rivers, and other water bodies. Groundwater flow interacts with surface water, contributing to baseflow and influencing stream hydrodynamics. Evaporation and transpiration

processes regulate water loss from the land surface and vegetation, modulated by climatic conditions and vegetation cover.

In conclusion, the CSM provides a holistic understanding of the environmental, hydrological, and socio-economic dynamics within the study area. By synthesizing data and mapping spatial relationships, the CSM serves as a valuable tool for guiding environmental management, land use planning, and sustainable development initiatives.

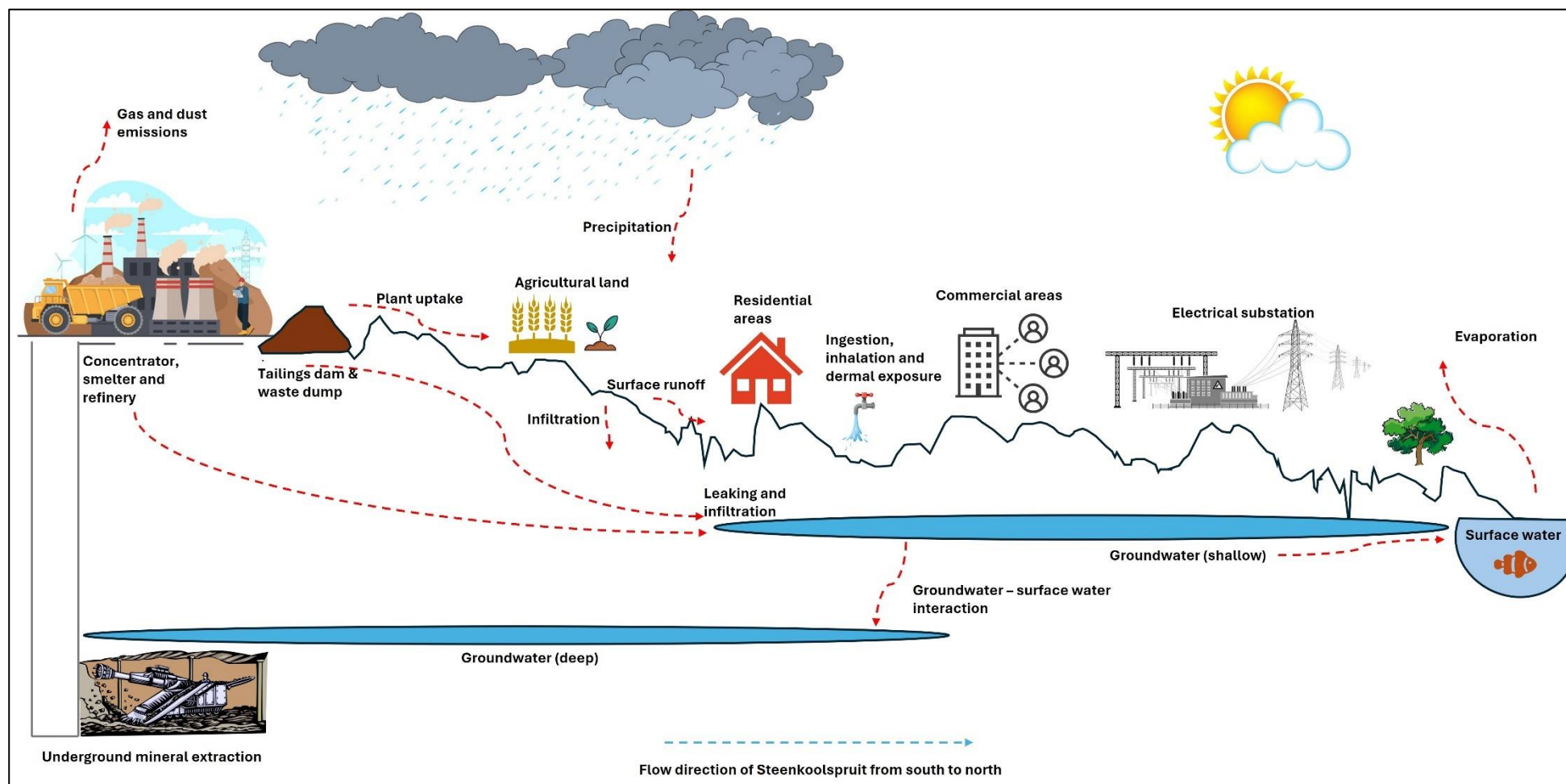


Figure 4-13 Site specific conceptual site model (Authors own, 2024)

4.8 Conclusion

In this chapter, the key features and history that render the study area intriguing have been emphasised. The impact of a century of coal mining on the natural water system in the study area and broader Mpumalanga province is intricate. The mining industry, while posing a threat to biodiversity and adversely affecting wetlands, has not only altered surface water but has also exerted significant pressure on water resources. Alterations in land use due to agricultural practices, mining infrastructure, and extensive coal-fired substations have modified the natural runoff coefficient, leading to diffuse pollution in the area.

The delineation of the study area, achieved by using DEM as a boundary for extracting necessary information, was discussed. Physical characteristics, encompassing vegetation, soil, and geology were identified during this process. Relevant data sources were then identified and processed based on the delineated catchment boundary. Special emphasis was placed on meteorological and hydrological data, including critical elements such as flow stations and rainfall gauges. Furthermore, the identification of key land cover features, such as agricultural activities, mining, and electricity infrastructure, was addressed.

The next chapter will engage in a detailed discussion of the data analysis.

CHAPTER 5

HYDROLOGICAL MODELLING WITH SWAT

5.1 Data Analysis

The data analysis is presented in the framework of the model selection discussed in Chapter 2 and the methodology outlined in Chapter 3. The data collected and analysed for the setup of the ArcSWAT model includes climate data, such as rainfall and streamflow, gathered up to the start of the project in 2022.

5.2 Hydrological data

5.2.1 Rainfall gauges and flow stations

The DWS website (2008) provided the records for rainfall and stream flow data for three rainfall gauges, namely B1E001, B1E004, and B1E005, in and around the study area. The rainfall stations are shown as triangles in Figure 5-1. Six flow stations were identified in the catchment, namely B1H005, B1H017, B1H018, B1H020, B1H021, and B1H022. The flow gauges are shown as circles in Figure 5-2.

When a rainfall and streamflow dataset has been identified, it is important to analyse the quality of such a dataset. Table 5-1 and Table 5-2 present the quality parameters for the DWS rainfall stations and streamflow gauges identified in the study, respectively. Rainfall station B1E001 had a high percentage of good continuous data for the time series as opposed to rainfall station B1E004, which had a low percentage (6.19%) of good continuous data. Both rainfall stations B1E004 and B1E005 had a high percentage of questionable data which indicated that the data may have had some issues or uncertainties, and users should exercise caution when using the data.

Regarding the flow gauges identified within the study area, B1H020 and B1H021 exhibited the highest percentage of good continuous data throughout the time series. In contrast, all other flow gauges also demonstrated a relatively high percentage of good continuous data throughout their respective time series. After careful examination, it was determined that B1H021 was the most suitable representation for the overall flow of the study area due to its positioning at the watershed outflow.

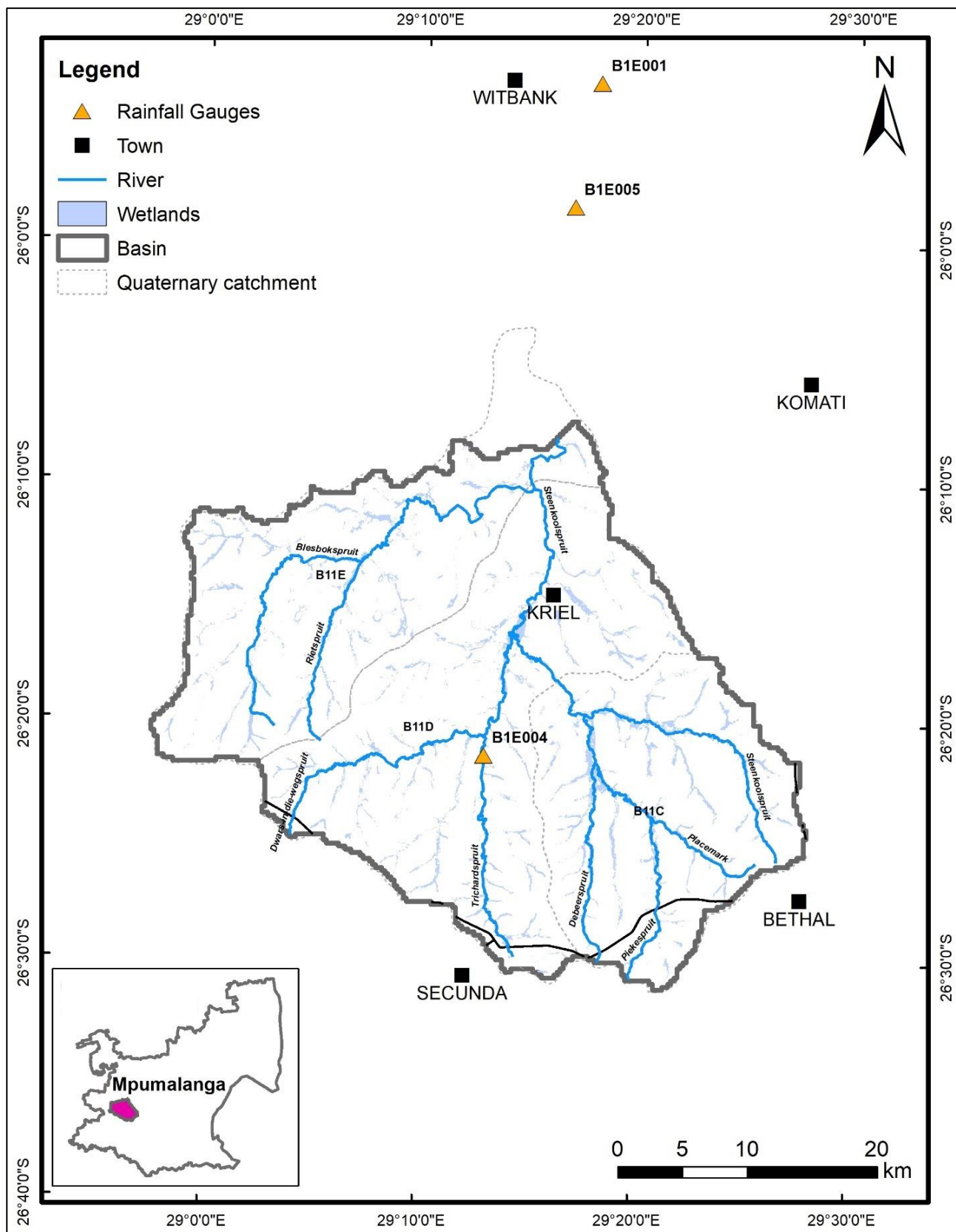


Figure 5-1 The DWS rainfall gauges in and around the study area (DWS, 2008)

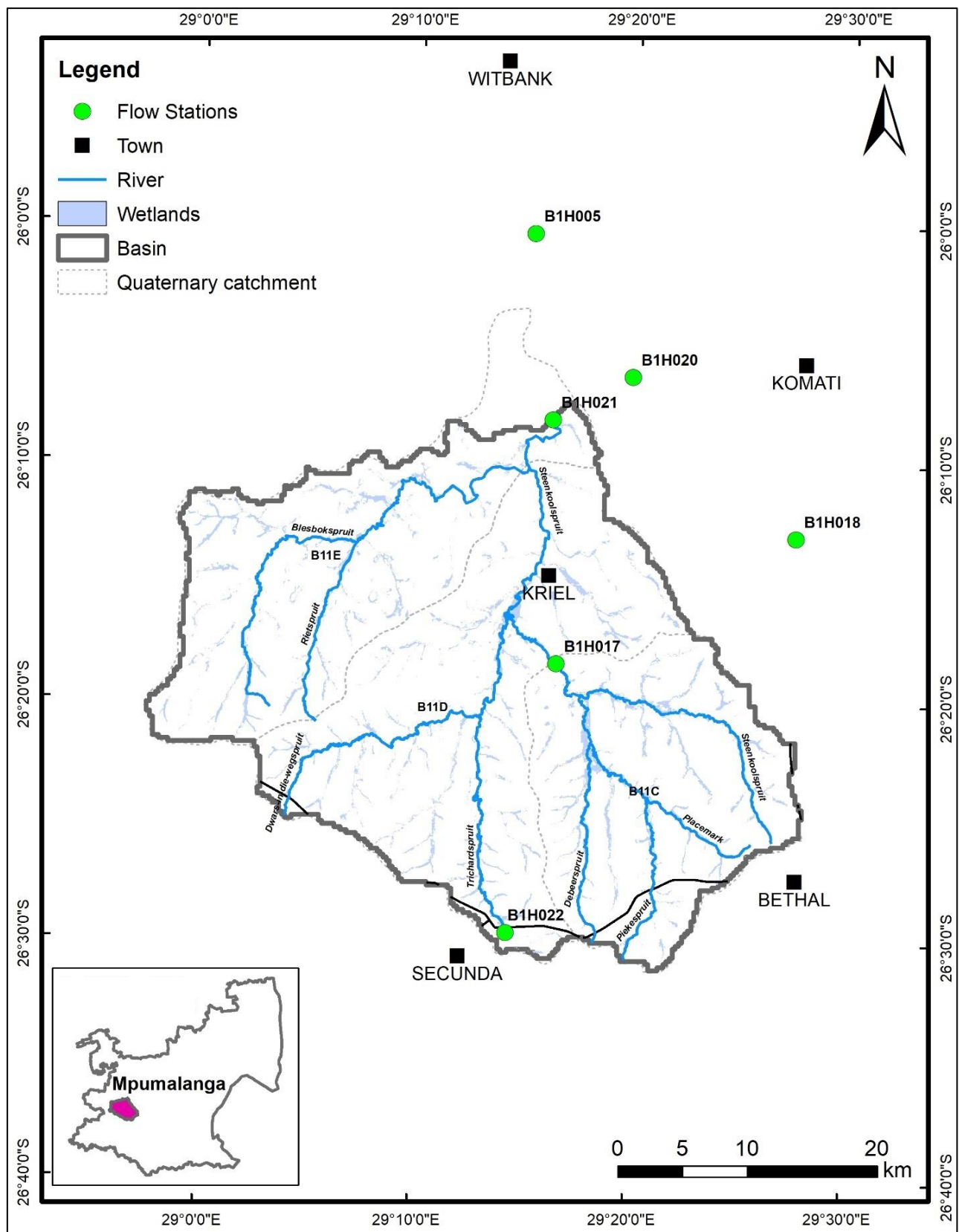


Figure 5-2 The DWS stream flow stations in and around the study area (DWS, 2008)

Table 5-1 Quality aspects for the rainfall gauges in and around the study area

Code	Description	B1E001		B1E004		B1E005	
		Count	%	Count	%	Count	%
1	Good continuous data	12 973	80.72	518	6.19	NA	NA
3	Preserved historical data	30	0.19	5 878	70.24	1 914	86.14
27	Good monthly reading	2 884	17.95	1 944	23.23	308	13.86
151	Data missing	NA	NA	25	0.30	NA	NA
170	Permanent gap	153	0.95	4	0.05	NA	NA
255	Data missing	31	0.19	NA	NA	NA	NA

NA = Not applicable to the gauge.

Table 5-2 Quality aspects for the flow stations in and around the study area

Code	Description	B1H005		B1H017		B1H018		B1H020		B1H021		B1H022	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
1	Good continuous data	13 765	76.02	6 380	54.18	6 303	53.25	4 987	85.81	5 701	86.71	7 927	69.65
2	Good edited data	3 064	16.92	4 306	36.57	5 220	44.10	NA	NA	776	11.80	2 870	25.22
5	Height derived from flow	NA	NA	NA	NA	35	0.30	NA	NA	NA	NA	NA	NA
47	Edited and checked – still unaudited	NA	NA	NA	NA	230	1.94	NA	NA	NA	NA	45	0.40
49	Checked estimate – still unaudited	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	515	4.52
60	Above rating	NA	NA	1	0.01	NA	NA	182	3.13	65	0.99	14	0.12
91	Minimum value	NA	NA	7	0.06	NA	NA	NA	NA	NA	NA	NA	NA
92	Maximum value	NA	NA	NA	NA	NA	NA	NA	NA	4	0.06	NA	NA
151	Data missing	2	0.01	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
170	Permanent gap	1 131	6.25	1 081	9.18	46	0.39	643	11.06	16	0.24	11	0.10
173	Data unreliable	144	0.80	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
255	Data missing	NA	NA	1	0.01	3	0.03	NA	NA	13	0.20	NA	NA

Notes:

NA = Not applicable to the station

5.2.2 Data comparison

Sections 4.5.1 and 4.5.2 illustrated the monthly availability of rainfall and stream flow data, highlighting the challenge of obtaining consistent monthly data for a given time series. Fortunately, the chosen ArcSWAT model permits both monthly and daily time steps, ensuring flexibility in accommodating data availability. The objective was to identify a rainfall gauge with the longest continuous long-term data and, most importantly, aligning its time series data with the identified flow station B1H021.

Based on the analysis of the data, flow station B1H021 and rainfall gauge B1E001 are deemed suitable for the rainfall-runoff model. Flow station B1H021 served as the outflow gauge for the entire study area, making it the most representative. Rainfall gauge B1E001 had the highest percentage of good continuous data (80.72%). Importantly, as shown in Figure 5-3, it possesses the longest overlapping time series with flow station B1H021. Notably, B1H021 also has the highest good continuous data (86.71%) among the other identified flow stations. This becomes significant when considering that the time series data will be divided into three periods: a reference period, a middle period, and a recent period, where the presence of good continuous data is pivotal.

Figure 5-3 illustrates the overlapping time series data for flow station B1H021 and rain gauge B1E001, divided into three time series for modelling. The time series data are divided as follows: reference period (1993–1997 [calibration]; 1998–2001 [validation]), a middle period (2002–2003), and a recent period (2004–2008).

The beginning of the reference period (1991–1993) includes a warm-up period where the model is allowed to stabilise and reach equilibrium before calibration begins. This helps ensure that the model is properly initialised and that initial transients do not influence calibration results. The longer reference period (1993–2001) is used for both calibration and validation. Having a longer reference period allows for a more robust calibration and validation process, increasing confidence in the model's accuracy. The recent period (2004–2008) is chosen to be comparable to the calibration period (1993–1997) in terms of duration (both are 5 years). This allows for a direct comparison of model performance between the reference period and the recent period. By using a consistent time frame, it can be determined whether the model's performance remains consistent over time or if there are any significant changes in the system being modelled. By including a middle period in the division of time series data helps to account for changes in climatic conditions and provides valuable insights into the model's performance across different temporal contexts.

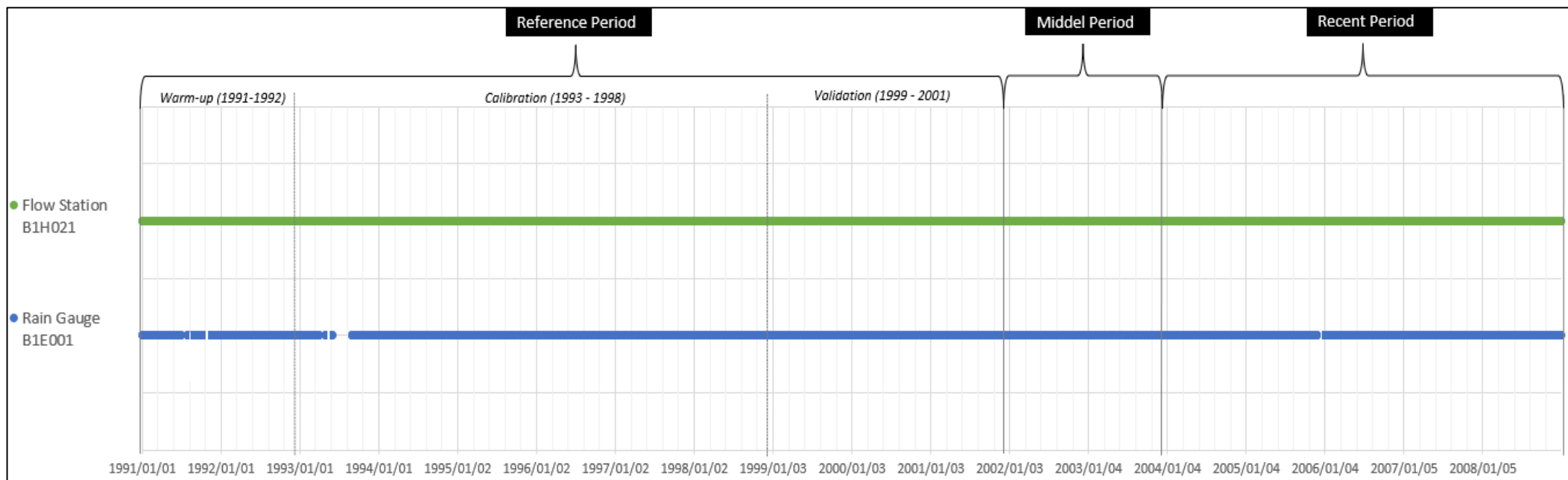


Figure 5-3 Overlapping time series data between flow station B1H021 and rain gauge B1E001, divided into three times series for modelling (1991–2008)
(Author's own, 2024)

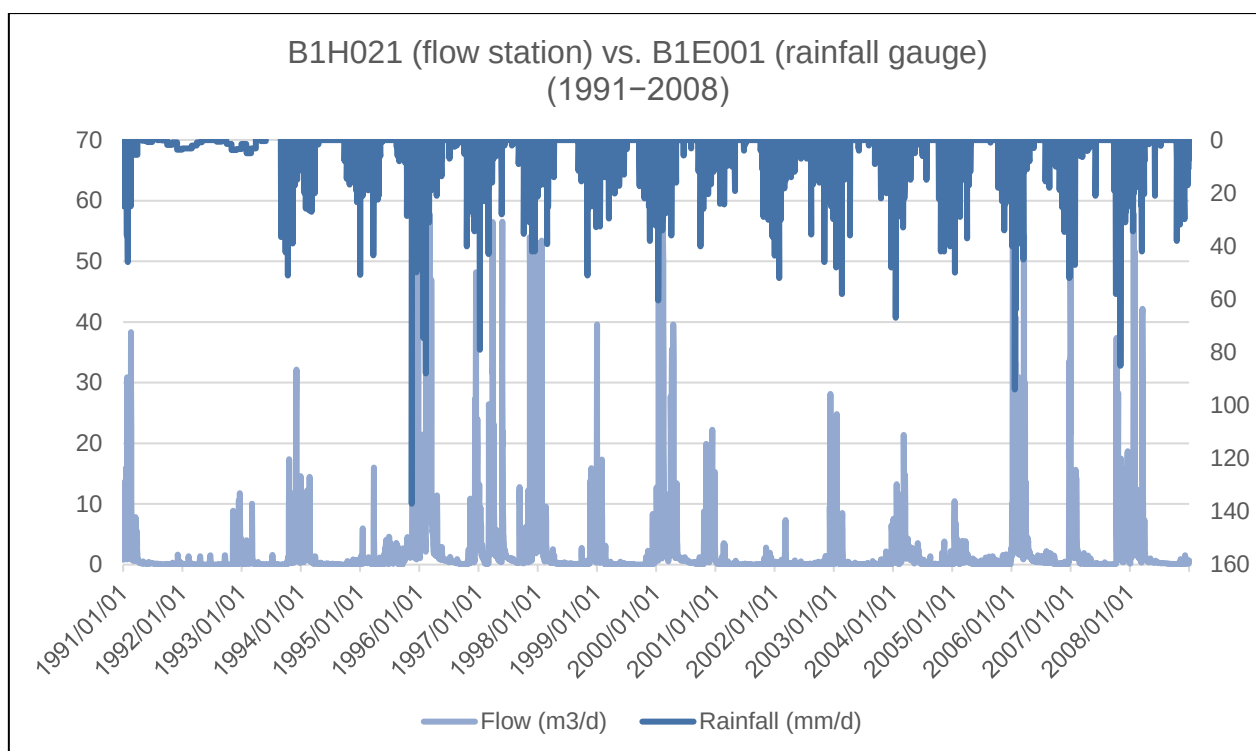


Figure 5-4 Data comparison between flow station B1H021 and rainfall gauge (Author's own, 2024)

Figure 5-4 illustrates the temporal distribution of rainfall gauge B1E001 and flow station B1H021 for a daily time step over a period of approximately 18 years.

There is no observed relative humidity, wind speed, or solar radiation data available in and around the study area. However, ArcSWAT has the functionality to generate this data from the weather generator embedded in the model. This function is very helpful for inputting missing data as well as generating data for a variable that was not measured in the catchment.

5.3 ArcSWAT model Setup

As highlighted in the preceding analysis, a thorough examination of historical data from various gauges, such as rainfall and flow, has provided essential insights into the climatic and hydrological dynamics of the study area. These insights serve as foundational elements for the subsequent setup of the ArcSWAT rainfall-runoff model. By integrating the temporal dimensions of the reference, middle, and recent periods, the approach ensures a comprehensive analysis that accounts for variations in environmental conditions over time. Building upon the methodologies discussed in previous chapters, the setup of the model involves careful consideration of parameter value ranges and a systematic process to ensure robustness and accuracy. In the following sections, the detailed setup of the ArcSWAT model will be discussed, as well as elucidating how these temporal dimensions will be incorporated and shedding light on the methodologies that will be employed to configure the model effectively.

During the construction of the ArcSWAT rainfall–runoff model, specific assumptions were made regarding the aspects of the catchment area (Table 5-3).

Table 5-3 Presuppositions related to the catchment area that could impact the model

Assumption	Calibration period (1993–1997)
Land cover	The land cover is assumed to be correct for the time period.
Uniform climate	The model may use uniform climate data across the entire watershed, assuming that climate conditions are the same for all locations within the watershed. This might not capture local variations in weather patterns.
Constant Mannings n	The Manning's roughness coefficient (n) in channel flow can be considered consistent throughout time. This simplification may not account for changes in channel roughness due to vegetation growth or other factors.

5.3.1 SWAT data input and acquisition

The ArcSWAT model was built for the reference period utilising the fundamental components of the established database as the foundation. The SWAT model input data include elevation (topography), land use, soil, and climate (weather) data, each playing a crucial role in simulating watershed processes. These inputs, outlined comprehensively in Table 4-2, serve as the building blocks for accurately representing the study area's hydrological dynamics.

To ensure spatial consistency and compatibility within the ArcSWAT framework, all spatially referenced inputs underwent geographic projection to the Universal Transverse Mercator (UTM), utilising the World Geodetic System 1984 (WGS84) datum system. This standardisation process guarantees seamless integration and alignment of disparate datasets, enabling the model to operate cohesively across various spatial layers.

The subsequent sections delve into the meticulous processing of each input dataset, elucidating the methodologies employed to acquire, preprocess, and integrate the data into the ArcSWAT model. From terrain characterisation to land cover classification and climate data interpolation, each step is meticulously documented to ensure transparency and reproducibility in the modelling process.

Appendix A illustrates the elements comprising the majority of the ArcSWAT interface related to project setup.

5.3.1.1 Watershed delineation

The SRTM90 dataset was used for the purpose of the watershed delineation, providing high resolution elevation data essential for accurately defining the catchment boundaries (Figure 4-3). The process of watershed delineation enables an accurate representation of the quaternary

catchment as well as the simulation of hydrological processes within quaternary catchments. This is necessary for evaluating a mining impacted catchment.

Since the exact location of the streams in the catchment is unknown, the delineation was done through the DEM-based option in the ArcSWAT program. This means that the SWAT model assigns streamflow paths based on the elevation values of the individual cells in DEM. In addition, the "Burn in" stream option was selected to further improve the hydrographic segmentation and sub-basin boundary delineation.

The model then generates sub-basins, which can be modified by the user. In this study, a threshold size of 5 000 ha for the sub-basins was specified. A threshold size of 5 000 ha was chosen for sub-basin delineation to strike a balance between capturing detailed drainage network features and maintaining computational efficiency. This value was determined through iterative testing and sensitivity analysis to ensure it adequately represented the catchments hydrological characteristics while remaining computationally feasible. Additionally, the threshold size was selected to optimise the trade-off between model complexity and computational resources, considering factors such as drainage network intricacies and processing time. The smaller the specified area, the more detailed the drainage network is, while a larger specified area leads to a less detailed network. The model created 15 sub-basins.

The decision for the DEM to generate 15 sub-basins was influenced by the automated criteria embedded within the ArcSWAT program. This built-in algorithm considers various factors such as terrain complexity, slope, and drainage patterns to determine the number of sub-basins. While this number may seem low, it reflects a balance between capturing essential hydrological features and avoiding excessive complexity that could hinder model calibration and computational efficiency. Additionally, the relevance of this criteria to the South African context suggests that it aligns with typical watershed characteristics found in the region, ensuring that the resulting sub-basins are representative of the study area's hydrology. At the end of the watershed delineation process, a watershed topography report was generated (Appendix B).

5.3.1.2 Land use, soil, and slope definition

SWAT uses land use, soil, and slope classes to determine the hydrological condition of the watershed. The land use data, a critical component in this regard, were generated from the DEA. For this study, the different land use classes were reclassified according to the SWAT land use classes found in the SWAT database (Table 5-4).

It is recommended, particularly for land use studies which should reflect a detailed land use, that the SWAT land use database be updated with data from the specific catchment (Winchell *et al.*, 2017). However, it was decided to utilise the SWAT database for land use classification in the SWAT model

primarily for its practicality and compatibility with the modelling framework, a choice further reinforced by the fact that it has not been extensively utilised in South Africa. While recognising the potential benefits of locally derived land use data, the SWAT database was used due to its comprehensive coverage of land use classes, which align closely with common land use types found in South Africa. This decision was motivated by the desire for efficiency in model setup and compatibility with existing SWAT methodologies. Additionally, the SWAT database offers a standardised classification scheme that facilitates seamless integration into the modelling workflow, streamlining the data preparation process and ensuring consistency in model inputs.

Table 5-4 Land use conversion from Digital Earth Africa land cover classes to the SWAT database classes

Digital Earth Africa land use classes	SWAT land use classes
Water permanent	Water – WATR
Wetlands	Wetlands-Mixed – WETL
Thicket / Dense bush	Pasture – PAST
Woodland / Open bush	
Grassland	
Low shrub land	Range bush – RNGB
Cultivated land	Agricultural Land-Row crops – AGRR
Plantations	Forest-Evergreen – FRSE
Mines	Industrial area – UIDU
Bare non-vegetated	Range grasses – RNGE
Urban	Urban – URBN

Waterbodies were classified as water. Wetlands were classified as Wetlands-Mixed. Thicket / Dense bush, Woodland / Open bush, and Grassland were classified as Pastures. Low shrub land was classified as Range Brush. Cultivated land was classified as Agricultural Land-Row Crops instead of Agricultural Land-Generic, since the majority of cultivated land in Mpumalanga is used for row crops, such as maize or soybeans. Plantations / Woodlots were classified as Forest-Evergreen as the plantations in the Mpumalanga province are known to be either pine plantations, wattle plantations or eucalyptus, which are all evergreen. Mines are classified as an industrial area. Bare non-vegetated land was classified as range grasses and urban areas were classified as residential. Even though Kriel consists of a wide variety of urban areas with different characteristics, the urban type that represented the highest percentage in the study area was the residential sector.

The 'Initial Soil Map of the World' was downloaded from the Food and Agriculture Organization (FAO) site in an ESRI shapefile format. Subsequently, the shapefile was imported to the ArcMap window and clipped to the extent of the study area. This layer displayed the FAO code corresponding to each soil type, integrating this FAO soil shapefile directly into the SWAT model posed a challenge as the model couldn't interpret these codes. Therefore, the FAO soil codes were entered into the database of the SWAT model. This process involved utilising 'MapWindow GIS' along with the MWSWAT software, which enabled the conversion of FAO soil codes into a format compatible with the MWSWAT database. Once converted, the MWSWAT dataset, now comprehending the FAO soil codes, was seamlessly integrated into the ArcSWAT database. Below is a table of the soil codes as displayed in the ArcSWAT database along with their description. Figure 4-7 illustrates the type of soil found in the study area.

Table 5-5 FAO soil codes that was entered into the SWAT model

Name in ArcSWAT database	Hydrological Group	Texture
Lc64-2b-722	C	Sandy Clay Loam
Vc1-3a-954	D	Clay

The last step before the overlay operations was performed was to identify the slope classes that would be used to establish the hydrological response units (HRUs). According to the SWAT user manual, this was deemed important if subbasins were known to have a wide range of slopes occurring within them (Winchell et al., 2017). The "Slope" tool from the Spatial Analyst toolbox in ArcMap was used to assign slope values (degrees) to each cell in the raster DEM. The number and range of slope classes depended on the specific requirements of the study and the characteristics of the landscape. For the study area, three slope classes were chosen – gentle (0.0-1.7 degrees), moderate (1.7-3.5 degrees), and steep (>3.5 degrees).

HRUs were then defined in the model after the reclassification process and the overlay of all three layers. The system subsequently produced a conclusive report on HRU distribution (Appendix C), delineating the distribution of land use, soil, and slope classes within each sub-basin of the watershed.

5.3.1.3 Hydrological response unit – Definition

After the data on land use, soil, and slope classes were combined in ArcSWAT, the identification of HRUs was necessary. HRUs represent areas with relatively uniform characteristics determined by the dominant land use, soil, and slope. The HRU definition could either be single or multiple. A single HRU represents an entire watershed or sub-watershed as a single unit. It assumes that the entire area within the HRU has uniform land use, soil type, and slope. In contrast, multiple HRUs divide the

watershed into smaller, discrete units, each representing a distinct combination of land use, soil type, and slope.

In this study, multiple HRUs were chosen, because multiple HRU modelling provides a more detailed and accurate representation of the watershed. This approach also helped to identify areas that have similar hydrological or water quality characteristics, which could be useful for targeting management or conservation practices. A threshold percentage of 10% was used to create HRUs. This was used to identify the boundaries that separate different units based on land use, soil type, and slope. The selection of the threshold value is contingent upon the goal of the research and the desired level of precision. In this study the level of detail required is high. This is because the catchment has a high degree of spatial heterogeneity in land use. A lower threshold percentage means that smaller areas of land with specific land use types will be considered as separate HRUs.

Part of the HRU definition was the Land Use Refinement, which is an optional function. This functionality allows for the specification of more detailed criteria. Typically, a specific land use can be split into two or several sub land use types. For example, the AGRL land use type can be split into two sub types: AGRL (50%) and AGRR (50%). This functionality was not applied since the initial land use definition achieved a satisfactory distribution.

5.3.1.4 Meteorological data

In ArcSWAT, the weather data refers to the meteorological information that is required as input for running the SWAT model. Weather data includes various meteorological factors such as rainfall, temperature, solar radiation, wind velocity, and moisture levels.

The weather data in ArcSWAT typically consists of daily or sub-daily (hourly) values for these climate variables. This high-resolution temporal data allows the SWAT model to simulate dynamic responses of the watershed to changes in weather patterns, facilitating accurate predictions of streamflow, groundwater recharge, and water quality parameters.

5.3.1.5 Weather data definition

The weather data definition refers to the step where the weather data are being imported to the model. It contains functions to build database files that include information needed to generate default input for the SWAT model. The commands on the menu need to be implemented only once for a project. However, if the HRU distribution is modified after building the input database files, these commands must be reprocessed again.

For the weather data definition, there is an option to either simulate the data in the model or to read from the data tables. If no observed weather data is available, then information can be simulated

using a weather generator. Daily precipitation values from the three rainfall gauges (B1E001, B1E004, and B1E005) in the catchment were loaded to the model. While the data from all three gauges were utilised for accuracy assessment, it is noteworthy that only the data from B1E001 were employed for calibration purposes. This data was used to estimate surface runoff, infiltration, and evapotranspiration. Minimum and maximum daily temperature data were added to the model, which are typically used to estimate average daily temperatures.

Other meteorological variables such as solar radiation, wind velocity, and humidity were not available for the study area. However, the weather generator function in ArcSWAT was used for generating data for the missing variable. This concluded the data importation of the model, and the writing of the input tables began. This facilitated the generation of essential input tables in ArcSWAT, serving as input files for the subsequent SWAT model simulation. These tables provided the model with the necessary data to simulate hydrological processes within the watershed.

The “Edit SWAT Input” functionality allows for the alteration of default SWAT input data. This menu can be used during the calibration process to make input modifications. While the "Edit SWAT Input" function offers valuable capabilities for modifying input data in ArcSWAT, its use depends on the specific requirements for the modelling of the study area, the quality of input datasets, and the level of expertise with GIS and hydrological modelling concepts. Consider the project goals, data availability, and modelling objectives this functionality was used to a limited extent.

5.4 SWAT Simulation Setup

The SWAT model was run for the reference period of eight years from 01-01-1991 to 12-31-1997. A monthly time step with a two-year warm-up period was used for the model. The first two years served as an initial period for the model to attain dynamic equilibrium before the commencement of the actual simulation phase. The warm-up period helped to ensure that the model captured the transient behaviour and stabilised the hydrological processes within the watershed. The SWAT model setup was done and then run (Figure 5-5).

As the simulation progressed, the SWAT model generated a wide range of outputs for the watershed at different scales. These outputs provided insights into the hydrological behaviour and the impacts of different factors within the watershed.

Setup and Run SWAT Model Simulation

Period of Simulation

Starting Date : Ending Date :

Min Date = 1/1/1991 Max Date = 1/2/2009

Rainfall Sub-Daily Timestep

Timestep: Minutes

Rainfall Distribution

☐ Skewed normal

☒ Mixed exponential

SWAT.exe Version

☐ 32-bit, debug ☐ 32-bit, release

☒ 64-bit, debug ☐ 64-bit, release

☐ Custom (swatUser.exe in TxtInOut folder)

Printout Settings

☐ Daily ☐ Yearly ☐ Print Log Flow ☐ Print Pesticide Output

☒ Monthly NYSKIP : ☐ Print Hourly Output ☐ Print Soil Storage

☐ Print Soil Nutrient ☐ Route Headwaters ☐ Print Binary Output

☐ Print Water Quality Output ☐ Print Snow Output ☐ Print Vel./Depth Output

☐ Print MGT Output ☐ Print WTR Output ☐ Print Calendar Dates

Output File Variables:

☐ Set CPU Affinity CPU ID:

Figure 5-5 Setup menu in ArcSWAT

The following chapter describes the process of model calibration and verification, involving the iterative adjustment of sensitivity parameters until the criteria for applicability evaluation were met. Finally, the model was used to simulate the spatial distribution of the river runoff.

CHAPTER 6

CALIBRATION AND VALIDATION

6.1 Calibration and validation process

Arnold *et al.* (2012b) described calibration as the process of adjusting parameters of a model to improve model performance to represent real-world conditions. In the case of SWAT, the calibration process involves comparing the model's simulated streamflow output with the observed data from the study area. The model parameters are iteratively tuned to minimise the discrepancy between the observed and simulated data. This process aims to find the best parameter values that will produce the closest match between the real-world data and the model outputs.

Validation is defined as the procedure of assessing the effectiveness of a calibrated model by employing a separate dataset that was not utilised in the calibration process (Arnold *et al.*, 2012b). The purpose of the validation process is to evaluate how capable the model is of making accurate simulations under different conditions or for different time periods.

The calibration and validation processes help to ensure the credibility and reliability of the SWAT model. Both procedures enhance the accuracy of the model and boost confidence in the outcomes.

6.2 Model performance evaluation criteria

A literature review was conducted to identify the recommended methods for assessing watershed model performance. Moriasi *et al.* (2007) described model evaluation techniques to facilitate watershed model evaluation. The guidelines and techniques mentioned in this research paper served as the commonly accepted reference for evaluating the performance of the SWAT model used in this study.

When evaluating the performance of a model, Moriasi *et al.* (2007) suggested that both quantitative statistical analysis and graphical techniques should be used to compare the simulated data to the observed data. Hence, graphical techniques and the following three quantitative statistics were used in this project: The Nash–Sutcliffe efficiency (NSE), the coefficient of determination (R^2) and percent bias (PBIAS).

The NSE is a measure used to assess the predictive capability of a hydrological model. It compares the observed data values, such as streamflow, with the simulated data values that the model generates. NSE ranges from negative infinity to 1 (1 inclusive), with 1 indicating a perfect match between observed and simulated data, while lower values indicate poorer or unacceptable model

performance. Moriasi *et al.* (2007) proposed that an NSE value of > 0.5 indicates that the model simulation is satisfactory, while values of ≤ 0.0 mean that the model performs as well as predicting the mean value of the observed data and is therefore an unsatisfactory model performance. NSE is calculated by the following equation:

$$NSE = 1 - \left[\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y_i^{mean})^2} \right]$$

The R^2 coefficient of determination, often referred to as R-squared, describes the goodness of fit between observed and simulated data (Moriasi *et al.*, 2007). R^2 ranges from 0 to 1, with lower values indicating a poorer model performance, and values of > 0.5 are satisfactory.

PBIAS assesses the inclination of the model to either underestimate or overestimate the observed data values, providing a numerical representation of the average tendency of the model to predict values that are either lower or higher than the actual observations. The PBIAS performance rating suggest that a percentage between 10% and 15% indicates a good performance, and a value of $> 25\%$ indicates an unsatisfactory performance (Moriasi *et al.*, 2007).

6.3 Calibration process

The effectiveness of model calibration significantly influences its ability to accurately simulate hydrological processes. The following sections will compare two primary approaches: manual calibration and semi-automated calibration.

As proposed by Arnold *et al.* (2012b), manual calibration follows an iterative process: (1) perform the simulation; (2) compare measured and simulated values; (3) assess the reasonableness of results using NSE/ R^2 /PBIAS values and flow pattern visualisations; if necessary, (4) readjust input parameters within reasonable ranges; and (5) repeat until satisfactory results are achieved. In this study, both calibration methods were employed not only to enhance calibration outcomes but also to ensure better control over parameter values for improved results. Manual calibration in ArcSWAT and auto-calibration in SWAT-CUP utilised six parameters based on insights from experts or experienced modelers (Arnold *et al.*, 2012b), alongside sensitivity analysis to identify parameters with the most significant impact.

6.4 Manual calibration

According to Balascio (cited by Moriasi *et al.*, 2007), in conventional practice, the calibration of hydrological models such as SWAT, is performed manually and involves adjusting the input parameter values to achieve simulated values that closely resemble the observed data within a

certain acceptable range. After the SWAT simulation was performed in ArcSWAT, manual calibration was done by comparing the simulated output, such as streamflow, with the corresponding observed data for the same time period.

This process involved gaining a good understanding of how the model structure and process works. Thereafter, key parameters were prioritised based on their impact on the variable of interest. The parameters that were used was selected based on experts or experienced modellers who could provide insights (Arnold *et al.*, 2012b) and by conducting a sensitivity analysis to identify the parameters with the greatest impact.

In the first step of the calibration process, parameters and parameter ranges was defined. Parameters that are expected to have great impact on hydrological processes and their ranges were chosen as given in Table 6-1. Thereafter, each of the nine parameters that was identified were manually calibrated until the R^2 values of the simulation results were acceptable, and the visual flow pattern closely resembled the observed flow pattern. In the initial stage of the manual calibration process, only R^2 was considered due to its initial simplicity, and it was the only optimal value that was achievable between the NSE, R^2 and PBIAS.

The values of these parameters were then manually modified in the ArcSWAT, starting with the most sensitive parameter, which was CN2, followed by other parameters to improve the R^2 value. The sensitivity ranks were obtained using manual calibration as depicted in Table 6-1. As the calibration progressed and sensitivity analysis was conducted, it became evident that multiple parameters, including NSE, R^2 , and PBIAS, were crucial for achieving optimal model performance. Then, an extensive review on previous studies were conducted to understand how increasing or decreasing the parameter's values affected the flow pattern, such as peak flow and baseflow. After hundreds of iterations using the manual calibration technique, the top six parameters (as ranked in Table 6-1) were chosen as the final parameter to be used in the semi-automated calibration process since they had the biggest contribution to improving the R^2 value.

Therefore, during the final run, all six parameters and the three evaluation techniques were incorporated to ensure comprehensive evaluation and refinement of the model. The results for the manual calibration are illustrated and further discussed in CHAPTER 7 Section 7.1.

Table 6-1 Parameters of sensitivity analysis obtained during manual calibration

Parameter	Parameter Range (Arnold <i>et al.</i> , 2012a)	Sensitivity mean value	Sensitivity rank
CN2 The Curve Number (CN) in SWAT estimates runoff potential based on soil and land cover characteristics (Xie <i>et al.</i> , 2020). CN2 specifically denotes the initial SCS runoff curve number for saturated or near-saturated soil conditions. It reflects the runoff potential when the soil is already saturated, resulting in increased surface runoff with additional rainfall.	35 - 98 (45)	0.440	1
SOL_K Soil hydraulic conductivity (SOL_K) establishes the speed at which water traverses the soil, influencing infiltration and drainage (Arnold <i>et al.</i> , 2012a).	0 – 2000 (500)	0.365	2
RCHRG_DP Fraction of percolation from the root zone that contributes to deep aquifer recharge is referred to as deep aquifer percolation recharge fraction (RCHRG_DP) (Arnold <i>et al.</i> , 2012a).	0 – 1 (0.05)	0.238	3
ESCO The soil evaporation compensation factor (ESCO) is the soil evaporation compensation factor in SWAT, modifying potential evapotranspiration based on soil moisture conditions. It effects the division of rainfall between surface runoff and infiltration. ESCO increases with higher soil moisture, allowing more rainfall to contribute to evapotranspiration. Conversely, lower ESCO values indicate lower soil moisture, reducing water available for surface evapotranspiration (Arnold <i>et al.</i> , 2012a).	0 – 1 (0.95)	0.149	4
SOL_AWC In SWAT, the soil layer water holding capacity (SOL_AWC) represents the available water capacity of a soil layer, indicating the maximum water that a soil layer can hold and provide for plant root extraction (Xie <i>et al.</i> , 2020).	0 – 1 (0.5)	0.065	5
GWQMN Minimum groundwater flow (base flow) threshold. It represents the minimum groundwater storage required to initiate groundwater flow in a HRU in the SWAT model (Arnold <i>et al.</i> , 2012a).	0 – 5000 (1000)	0.045	6
ALPHA_BF The recession rate of baseflow from groundwater storage after a runoff event (Arnold <i>et al.</i> , 2012a).	0 – 1 (0.048)	0.012	7
GW_DELAY Delay in groundwater response to changes in precipitation or recharge events (Arnold <i>et al.</i> , 2012a).	0 – 500 (32)	0.001	8
SURLAG The lag time between the occurrence of rainfall and the initiation of surface runoff (Arnold <i>et al.</i> , 2012a).	0.05 – 24 (2)	0.001	9

6.4.1 Parameter ranges

In a mining-impacted catchment, understanding the implications of parameter ranges is crucial for effective hydrological modelling and watershed management. As outlined by Arnold *et al.* (2012a), the parameter ranges, such as the Curve Number for impervious areas (CN2) dictates the surface runoff response, with lower values indicating greater infiltration potential, typical of undisturbed areas, while higher values signify increased imperviousness, often found in areas with extensive mine infrastructure. The Groundwater Delay (GW_DELAY) parameter influences the timing of groundwater response to recharge events, with lower values suggesting immediate response, potentially affected by mine dewatering activities. Conversely, higher GW_DELAY values indicate delayed groundwater response, which may be observed in areas with intact aquifer systems. Surface Runoff Lag Time (SURLAG) determines the delay between rainfall and runoff initiation, where lower values suggest rapid runoff response, possibly due to altered surface conditions in mining areas. Meanwhile, higher SURLAG values imply prolonged lag times, indicating delayed runoff response and potential sedimentation issues. Soil Hydraulic Conductivity (SOL_K) influences water movement through the soil profile, with lower values indicating restricted infiltration, possibly due to soil compaction from mining activities. Higher SOL_K values suggest improved infiltration potential, often found in undisturbed soils. Baseflow recession (ALPHA_BF) governs the rate of groundwater contribution to streamflow, where lower values imply sustained baseflow, typical of areas with high groundwater storage or recharge rates. Higher ALPHA_BF values indicate rapid baseflow recession, which may be influenced by mine dewatering or altered flow paths. Overall, understanding parameter ranges in a mining-impacted catchment helps tailor hydrological models to reflect the complex interactions between mining activities, land use changes, and natural watershed processes.

6.5 Semi-automated calibration using sequential uncertainty fitting, version 2 (SUFI-2) in SWAT

SWAT-CUP is a program that integrates with ArcSWAT and provides a more streamlined approach to calibration, which saves time and reduces the frustration of manual calibration (Abbaspour, 2014).

SWAT-CUP incorporates a semi-automated method (SUFI-2) which utilises both automated and manual calibration integrating uncertainty and sensitivity analyses (Arnold *et al.*, 2012b). The SUFI-2 program requires the user to manually adjust parameters during some steps of the calibration process. Users can also leverage the outputs from uncertainty and sensitivity analyses by iteratively transitioning between automated and manual calibration. Uncertainty analyses provide statistics for evaluating the goodness-of-fit, and parameter sensitivity analyses aids in identifying influential parameters and thereby helps the focus of the calibration.

6.5.1 Sensitivity analysis in SUFI-2

Sensitivity analysis is an important step in the calibration and validation process. It helps to govern which model parameters have the greatest impact on the model output and can help to reduce the uncertainty in model predictions (Arnold *et al.*, 2012b). There are two types of sensitivity analysis that exist, namely local (one-at-a-time) sensitivity analysis and global sensitivity analysis. The one-at-a-time method focusses on varying each parameter one at a time, while keeping all other parameters fixed at their baseline values. The impact or sensitivity of a particular parameter in a model can be influenced by the values of other related parameters (Arnold *et al.*, 2012b), which can be a problem with local sensitivity analysis. Global sensitivity analysis, on the contrary, considers the effects of simultaneously varying all parameters over their entire range. Global sensitivity analysis is more computationally intensive than local sensitivity analysis but provides a more holistic view of the influence that parameters can have, and it is valuable when dealing with a larger number of parameters (Arnold *et al.*, 2012b). Hence, global sensitivity analysis was performed in this study.

6.5.2 SUFI-2 calibration

Calibration is the act of adjusting the model input parameters to improve its performance and accurately represent the real-world system by matching the model output with observed data (Arnold *et al.*, 2012b). It means that by adjusting the model's parameters to closely fit the observed data, calibration helps reduce the uncertainty in the model's predictions, making it a more valuable tool for making informed decisions.

Input parameters should be carefully selected based on the most important and influential parameter in the model. This can be done by either performing sensitivity analysis or by means of expert judgement (Arnold *et al.*, 2012b). For this study area, both approaches were used to adjust the model parameters. First, common practices used in previous studies were considered to fine-tune the parameters. Second, the global sensitivity analysis conducted in SUFI-2 was used to identify the most influential parameters and further refine their values. Table 6-2 indicates the parameters used during the calibration process in specific SWAT watershed studies (Arnold *et al.*, 2012b).

Table 6-2 Calibration parameters chosen in accordance with specific SWAT watershed studies

Process		Input parameters	Number*
Surface runoff	CN2	Runoff curve number	36
	AWC	Available water capacity	28
	ESCO	Soil evaporation compensation factor	23
	EPCO	Uptake compensation factor	10
	SURLAG	Coefficient of surface runoff delay	22
	OV_N	Manning's Roughness for Overland Flow	8
Baseflow	GW_ALPHA	Groundwater alpha factor	28
	GW_REVAP	Groundwater 'revap' coefficient	18
	GW_DELAY	Groundwater delay time	21
	GWQWN	Minimum groundwater flow (base flow) threshold	12
	REVAPMN	Threshold depth of water in the shallow aquifer for "revap"	13
	RCHARG_DP	Deep aquifer percolation recharge fraction	14

* The number denotes the frequency of the utilisation of the parameters in the calibration process (Adapted from Arnold *et al.*, 2012b)

During the SUFI-2 program setup process, the *objective function* is specified by the user. This serves as the statistical measure to evaluate the performance of the calibrated and validated results. In this study, the NSE objective function was chosen, with a criterion of $NSE > 0.5$.

The parameters selected for the calibration in SWAT-CUP, along with their initial ranges and method of adjustment, are detailed in

Relative (r_) denotes the current parameter value, which is multiplied by 1, plus a specified value. Replace (v_) designates the current parameter value that needs to be substituted with the provided value. The adjustment parameter method that was used during the initial iteration is shown in the Table 6-3.

Table 6-3. The adjustments that were made to the parameters followed the guidelines provided in the "Parameterisation in SWAT-CUP" section of the SWAT-CUP user manual (Abbaspour, 2014):

Relative (r_) denotes the current parameter value, which is multiplied by 1, plus a specified value. Replace (v_) designates the current parameter value that needs to be substituted with the provided value. The adjustment parameter method that was used during the initial iteration is shown in the Table 6-3.

Table 6-3 The initial SWAT parameter ranges used in the SWAT-CUP program SUFI-2

Parameter*	Description	Range		Change
		Min	Max	
Surface response				
CN2.mgt	Soil Conservation Services: Runoff curve number	35.00	98.00	Replace
ESCO.hru	Factor for compensating soil evaporation	0.00	1.00	Relative
SOL_AWC.sol	The water retention ability of the soil layer (mm H ₂ O/mm soil)	0.00	1.00	Relative
SOL_K.sol	Saturated hydraulic conductivity (mm/h)	0.00	200.00	Replace
Subsurface response				
GWQMN.gw	Minimum water depth in the shallow aquifer necessary for the initiation of return flow (mm H ₂ O)	0.00	5 000.00	Replace
Basin response				
RCHARG_DP.gw	Fractional percolation in deep aquifer	0.00	1.00	Relative

* CN2 = Runoff curve number; ESCO = Soil Evaporation Compensation Factor; SOL_AWC = Soil layer's water holding capacity; SOL-K = Soil hydraulic conductivity; GWQMN = Minimum groundwater flow (base flow (threshold); RCHARG_DP = Deep aquifer percolation recharge fraction; .mgt = management; .hru = hydrological response unit; .sol = soil; .gw = groundwater.

6.5.3 Validation

The validation process involves the assessment of the calibrated SWAT model by using a dataset of a different period (Arnold *et al.*, 2012b). It means that the validation process demonstrates that the calibrated model does not over-fit the calibrated data and is capable of making accurate predictions under different conditions. These authors highlighted that it adds a level of confidence to the model's performance and its capability to be used in scenario analysis and decision-making.

The validation period for the project was from the years 1998–2001. During the validation process, the parameter range stayed the same as during the calibration process and a single iteration of the same number of simulations was used, which was 50.

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Manual calibration results

From Figure 7-1 it is evident that for the high rainfall events, the observed flow was higher than the simulated flow, whereas, for lower rainfall events the simulated flow was higher than the observed flow. This suggests potential inaccuracies in some initial parameter values. This observation aligns with the model performance criteria, showing an NSE coefficient of -0.31 and an R^2 value of 0.73 . The PBIAS, measured as -1.18 , clearly confirmed that calibration was needed.

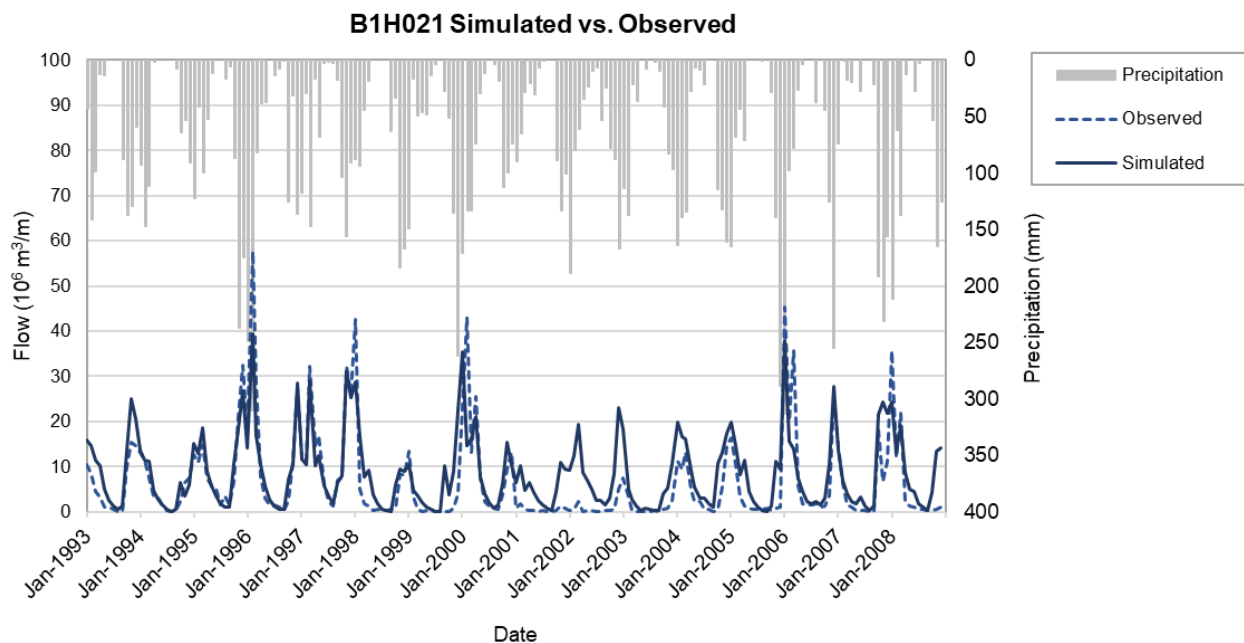


Figure 7-1 Manual calibrated simulation runoff for flow station B1H021

The manual calibration attempts yielded acceptable results for R^2 . Considering the successful manual calibration for one of the three performance evaluation criteria of the SWAT model, and given the reliability of the results, the availability of high-quality observed data, and alignment with project objectives, it was decided to proceed with a semi-automated calibration. This decision was made based on the potential for further fine-tuning model parameters revealed in sensitivity analysis, which may enhance the accuracy of the model and better meet the specific needs of the project. Despite the additional resources and time required for semi-automated calibration, it represented a valuable step to ensure the utmost precision in modelling outcomes. The 2012 version of ArcSWAT does not include an automated calibration function to calibrate the model. Hence, the SWAT-CUP 2012 software was downloaded and utilised as an alternative for automated calibration within the

ArcSWAT modelling framework. The application of SWAT-CUP was intended to enhance the resilience of the model and foster a deeper insight into the hydrological processes within the research area. This, in turn, boosts confidence in the predictions of the model and its utility for water resources management and decision-making.

7.1.1 Global sensitivity analysis results using SUFI-2

SWAT-CUP includes multiple algorithms of which Sequential Uncertainty Fitting, version 2 (SUFI-2) has shown to be one of the most effective algorithms in identifying sensitive parameters (Glavan & Pintar, 2014). Sensitivity analysis can assist in the exclusion of non-sensitive parameters from the calibration procedure. The global sensitivity analysis outcome that was performed in SUFI-2 is shown in Table 7-1. T-statistic (t-stat) and p-statistic (P-value) are used in SWAT CUP to determine how significant a calibrated parameter is. The t-statistic measures the difference between the estimated parameter value and zero, where a high t-statistic means that it has a larger impact on the performance of the. The p-statistic reflects the importance of sensitivity, with a low p-value (below a predetermined significance level, such as 0.05) indicating increased significance of the parameter.

The sensitivity analysis revealed that CN2, or runoff curve number, as well as SOL_K are the most sensitive parameters (p-value = 0). Therefore, through the course of the calibration process, more emphasis was placed on these parameters. The calibration procedure commenced with CN2, involving minor adjustments to CN2, while maintaining constant values for all other model parameters during the run. Following the examination of various CN2 values and the observation of their impact on runoff volume and peak flow, the model parameters were reverted to their original values. Subsequently, the process was repeated for the next model parameter (SOL_K), with incremental adjustments and careful monitoring of its impact on runoff and peak flow. This iterative approach was applied to all sub-catchment model parameters. All remaining parameters also showed considerable sensitivity (p-value approaching or equalling zero), resulting in also including them during the calibration process. A sensitivity analysis was conducted by systematically changing individual parameters one at a time, while considering that the value of one parameter frequently depends on the values of the other related parameters.

The iterative calibration process involved adjusting these sensitive parameters while closely monitoring their effects on model outputs, such as runoff volume and peak flow. This iterative approach allowed for fine-tuning the model to better represent observed hydrological behaviour.

Table 7-1 Global sensitivity analysis results

Parameter	<i>t</i> Stat	<i>P</i> value
CN2.mgt	-15.816	0.000
SOL_K.sol	-3.961	0.000
RCHRG_DP.gw	-2.661	0.013
ESCO.hru	0.715	0.481
SOL_AWC.sol	0.548	0.588
GWQMN.gw	-0.115	0.909

* CN2 = Runoff curve number; SOL-K = Soil hydraulic conductivity; RCHARG_DP = Deep aquifer percolation recharge fraction; ESCO = Soil evaporation compensation factor; SOL_AWC = Soil layer's water holding capacity; GWQMN = Minimum groundwater flow (base flow) threshold; .mgt = management; .sol = soil; .gw = groundwater; .hru = hydrological response unit.

The overall reliability of the simulation results is likely to be high, given the comprehensive sensitivity analysis and iterative calibration process undertaken. The use of SUFI-2, a robust algorithm for identifying sensitive parameters, enhances the credibility of the sensitivity analysis results. The iterative calibration process, focusing on adjusting highly sensitive parameters such as CN2 and SOL_K, demonstrates a rigorous approach to refining the model and improving its performance. The consideration of statistical measures such as t-statistic and p-value in SWAT-CUP provides quantitative insights into the significance of calibrated parameters, further enhancing the reliability of the calibration process.

By systematically adjusting individual parameters while considering their interdependencies, the sensitivity analysis ensures a thorough exploration of parameter space, leading to a more robust calibration of the model. Overall, the detailed sensitivity analysis and calibration process contribute to the overall reliability of the simulation results by enhancing the model's ability to accurately represent the observed hydrological processes and dynamics within the study area.

7.2 Uncertainty analysis in SUFI-2

The findings and subsequent discussion are closely linked to the notion of uncertainty within the SUFI-2 modelling process, which acknowledges and supports the accuracy of the results. The calibration process aims at refining parameter values for a specific area, ultimately reducing the predictive uncertainty (Arnold *et al.*, 2012b). This following chapter will delve into the concept of uncertainty and how it integrates into SUFI-2. Subsequently, an examination will be conducted on the application of uncertainty during the calibration of the modelled study area.

7.2.1 Uncertainty of the modelling process of SUFI-2

Uncertainty is a critical aspect of the modelling process (Abbaspour, 2014; Arnold *et al.*, 2012b; Moriasi *et al.*, 2007). Uncertainty can arise in several ways within the context of SUFI-2, which can be in the model itself, stemming from the approximations in the mathematical equations employed to simulate the process (Moriasi *et al.*, 2007). Uncertainty can arise from the quality of input data used to drive the model (Abbaspour, 2014; Moriasi *et al.*, 2007). This data includes climate, soil, and land use. Additionally, uncertainty may result from a lack of knowledge in understanding the underlying physical processes and operational procedures while conducting the modelling (Moriasi *et al.*, 2007). Hereby Moriasi *et al.* (2007) suggested that while effective model calibration is important for minimising discrepancies in model output, empirical evidence shows that model simulation outcomes may still include significant inaccuracies.

7.2.2 How does SUFI-2 account for the uncertainties

In SUFI-2, uncertainty is conceptually addressed and quantified in several ways such as parameter uncertainty (climate variables), input data uncertainty, model structure uncertainty, prediction uncertainty and sensitivity analysis. The degree to which all these uncertainties are addressed and accounted for is quantified by two measurements called the P-factor (Percent factor) and R-factor (Relative factor).

The P-factor is used to represent the range of parameter values within which the model is allowed to vary during the calibration process (Abbaspour, 2014). It serves as a measure of the robustness of the uncertainty analysis and calibration process. A higher P-factor indicates a wider range of parameter values, which provides greater uncertainty when estimating parameters. On the contrary, the R-factor denotes the distinction between the predictions of the model and the actual observed data (Abbaspour, 2014). A higher R-factor allows for more weight to be assigned to minimising the residuals during calibration, meaning the model is closely fitted to the observed data.

The intent of SUFI-2 is to range as much as possible of the measured data within the 95% prediction uncertainty (95PPU) band. It starts out by establishing a broad range of uncertain parameters, emphasising the insurance of physical relevance, to include all initially recorded data within the 95th percentile range. The uncertainty is incrementally reduced while monitoring the change in the P- and R-factor. The parameter ranges are subsequently updated to a range that is always smaller than the preceding range, within the previous iteration (Abbaspour, 2014).

In SUFI-2, when a simulation exactly corresponds to the observed data, a P-factor with the value of 1 and an R-factor with a value of 0 will be achieved (Tang *et al.*, 2012). Hence, a larger P-factor value and a smaller R-factor value indicate a simulation with less uncertainty.

7.3 Reference period results

Multiple simulation runs were conducted to achieve results that demonstrate both visually and statistically favourable outcomes, showing simulated runoff volume and peak flow in alignment with the observed values. The calibration results are presented in accordance with the calibration process of the flow gauge B1H021. The conclusive model parameter ranges obtained from calibration are detailed in Table 7-2 . The table represents the final parameter ranges that were used in SUFI-2, which provided adequate values for the P-factor and the R-factor. Following the identification of the parameter value ranges (P-factor and R-factor) a few more iterations were run but were less optimal when comparing the criteria. Therefore, the parameter ranges in Table 7-2 were consistently applied, not only in the validation run, but also in the second and third models, as discussed in section 3.1. The results for the second and third models are displayed in section 7.4.1.

Table 7-2 Calibrated parameter range for the final iteration run during the calibration of SUFI-2 which produced adequate values for the criteria (P-factor and R-factor)

Parameter name*	Calibrated parameter range	
	Minimum	Maximum
CN2.mgt	68.806	89.523
SOL_K.sol	-0.882	2.073
RCHRG_DP.gw	0.327	0.805
ESCO.hru	0.139	0.344
SOL_AWC.sol	0.764	1.062
GWQMN.gw	0.309	0.929

* CN2 = Runoff curve number; ESCO = Soil evaporation compensation factor; GWQMN = Minimum groundwater flow (base flow) threshold; SOL-K = Soil hydraulic conductivity; SOL-AWC = Soil layer's water holding capacity.

The graphical presentation for the final calibration run during the reference period (1993–1997) in SUFI-2, which yielded significantly improved results compared to the manual calibration, is displayed in Figure 7-2. From this figure, the simulation accurately simulated the majority of peak flows, but the third and fourth peaks were less accurately simulated. Specifically, the rising and falling portions of the flow of the fourth peak were less accurate than the observed. As there were no alterations in land use and vegetation cover, the variation in runoff between the two peaks was primarily influenced by differences in precipitation levels.

In Figure 7-3, the lower and upper 95PPU lines are illustrated as in SUFI-2, and the green area between the lines are the 95PPU band, indicating the R-factor. An R-factor of 0.38 was achieved

(out of a perfect 0), where an R-factor below 1 indicates a narrow 95PPU band. A 0.52 (out of a perfect 100%) P-factor means that 52% of the observed monthly flow values was captured by the 95PPU band.

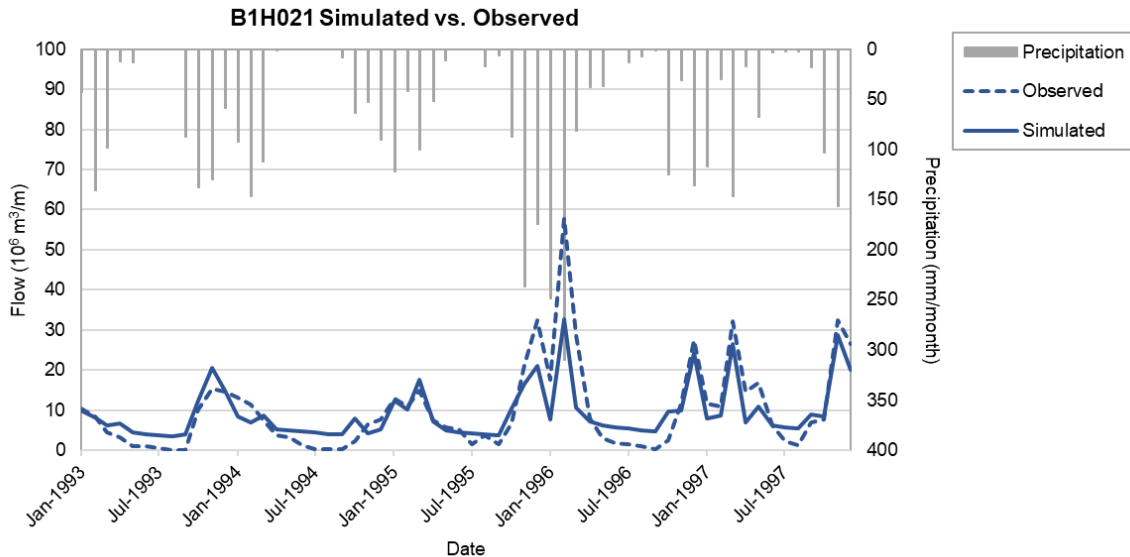
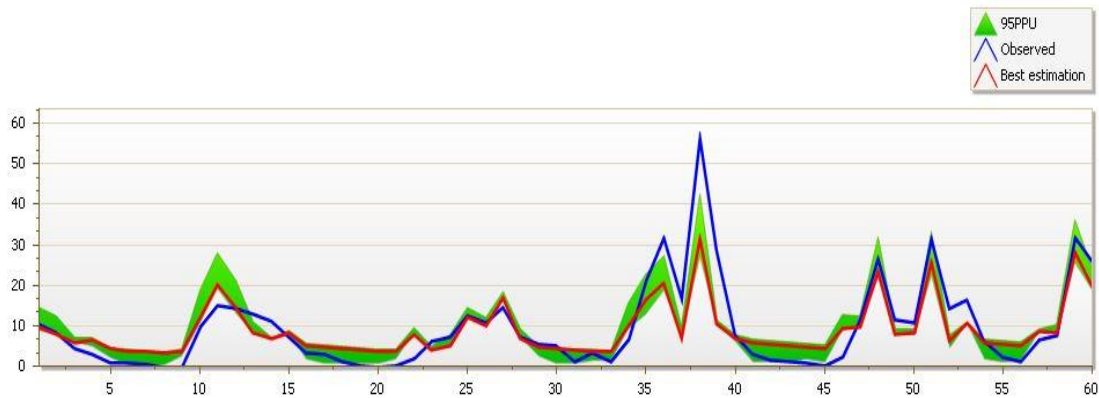


Figure 7-2 Calibration results for the simulated versus observed flow gauge B1H021 during the reference period (1993–1997)



Note: The 95PPU band illustrates the R-factor

Figure 7-3 Calibration results for the simulated versus observed flow gauge B1H021 during the reference period (1993–1997) as displayed in SUFI-2

The validation results, utilising the calibration parameter range, are shown in Figure 7-4. In Figure 7-4, the validated runoff shape and peak flow demonstrates a good resemblance with the observed runoff shape and peak flow. The simulated base flow is more than the observed base flow, especially for the last year of the validation period. This discrepancy suggests that the model may be overestimating the contribution of base flow to the total flow, potentially due to inaccuracies in representing groundwater dynamics or other hydrological processes affecting base flow generation.

This discrepancy could be associated with the parameters concerning base flow generation in the model, including groundwater storage and recession coefficients.

Figure 7-5 similarly illustrated the lower and upper 95PPU lines as with the calibration period. The validation results revealed that 15% of the observed data fell into a lower 95PPU band when compared to the calibration results. An achieved R-factor of 0.23 (out of a perfect 0) suggests reduced uncertainty in the simulation.

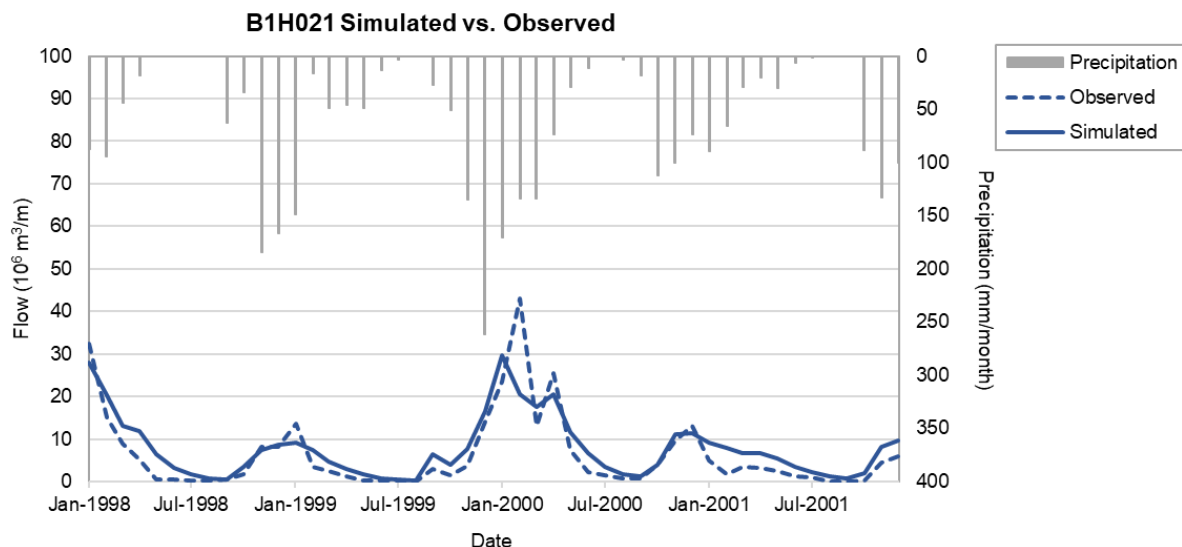
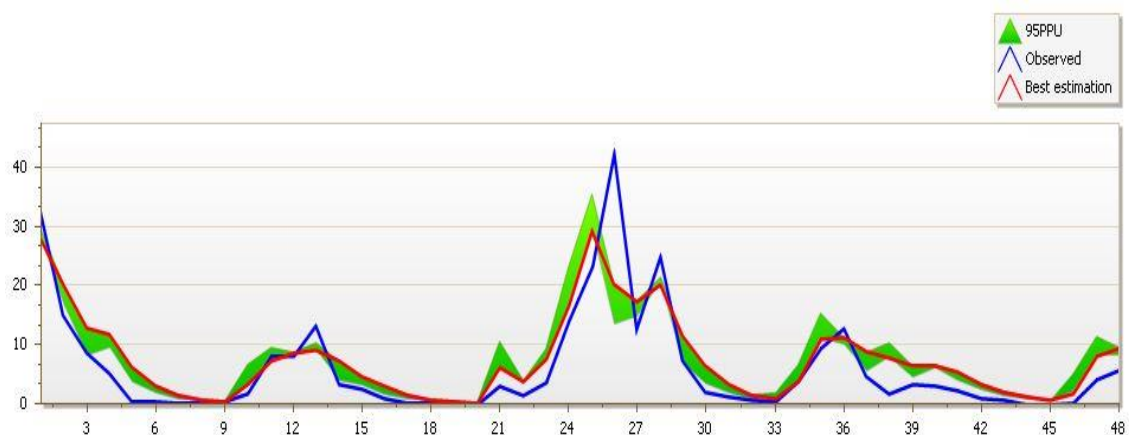


Figure 7-4 Validation results for the simulated versus observed flow gauge B1H021 during the reference period (1998–2001)



Note: The 95PPU band illustrates the R-factor

Figure 7-5 Validation results for the simulated versus observed flow gauge B1H021 during the reference period (1998–2001) as displayed in SUFI-2

The good correlation in the figures above are supported by the model performance evaluation criteria in Table 7-3. The table displays the outcomes of assessing the performance of the model throughout

the calibration and validation phases. The discharge values, both observed and simulated, are averages. These results suggest that the SWAT model effectively captures the Steenkoolspruit runoff dynamics for the specified reference period.

Table 7-3 Model performance evaluation results during the calibration (1993–1997) and validation (1998–2001) periods

Periods	Observed value (10 ⁶ m ³ /m)	Simulated value (10 ⁶ m ³ /m)	NSE	R ²	PBIAS
Calibration (1993–1997)	8.52	9.291	0.73	0.82	6.1
Validation (1998–2001)	6.601	8.518	0.77	0.77	-23.8

Achieving specific thresholds for NSE, R², and PBIAS is crucial for assessing the accuracy and reliability of hydrological models. These performance metrics provide quantitative measures of how well the model's simulated outputs match observed data.

NSE compares the observed data variance with the variance of the residuals (difference between observed and simulated values), relative to the variance of the observed data. It ranges from negative infinity to 1, where 1 indicates perfect agreement between observed and simulated values. Achieving a positive NSE value indicates that the model performs better than a simple mean estimation. However, specific threshold values for NSE can vary depending on the complexity of the system and the quality of observed data. Generally, NSE values greater than 0.5 are considered acceptable for many hydrological applications.

R² measures the proportion of the variance in the dependent variable (observed data) that is predictable from the independent variable (simulated data). It ranges from 0 to 1, where 1 indicates perfect correlation between observed and simulated values. Achieving an R² value close to 1 suggests a strong relationship between observed and simulated data. However, R² alone may not capture the accuracy of predictions, especially when dealing with non-linear relationships or heteroscedasticity (unequal variances). In hydrological modelling, R² values above 0.5 are often considered satisfactory, but like NSE, specific threshold values can vary based on the application and data quality.

PBIAS measures the average tendency of the simulated values to be larger or smaller than the observed values, expressed as a percentage of the observed values. Achieving a PBIAS value close to 0 indicates that the model does not systematically over- or underestimate the observed data. However, PBIAS does not provide information about the direction of bias; positive values indicate

overestimation, while negative values indicate underestimation. In practice, PBIAS values between 10% and 15% are often considered acceptable, although specific threshold values may vary depending on the application and stakeholder requirements.

In summary, achieving specific thresholds for NSE, R^2 , and PBIAS is indicative of the model's accuracy and reliability in replicating observed hydrological processes. These metrics provide valuable insights into the model's performance and its ability to inform water resources management decisions effectively.

The model performance evaluation between the simulated and observed flow values, in terms of quantitative statistics, was modelled with NSE, R^2 , and PBIAS criteria. During the setup of the model in SUFI-2, an NSE objective function of > 0.5 was specified. An achievable NSE of 0.73 was achieved during calibration. According to Moriasi *et al.* (2014), a performance rating of $NSE > 0.5$ is considered good. The results for R^2 and PBIAS from the SUFI-2 calibration are also considered good, which indicate that the calibrated simulated data and the observed data have a strong correlation. Similarly, the NSE and R^2 correlation for the validation period are very strong (> 0.75). The negative PBIAS results for the validation suggest that the value is better predicted than simulated, which means an unacceptable model performance. The PBIAS for the validation was -23.8% , which is unsatisfactory.

The results of the model are considered acceptable based on quantitative statistics such as NSE, R^2 , and PBIAS, meeting or exceeding predefined criteria. Additionally, a visual inspection and event-based analysis supported the performance of the model. Sensitivity analysis and consistency across multiple criteria further enhanced confidence. However, attention is needed for the negative PBIAS during the validation period. Overall, considering the comprehensive evaluation, the model demonstrated satisfactory performance, validated by various approaches and criteria.

7.4 Calculation of water reduction in the recent period

In numerous locations, it is anticipated that climate change may considerably reduce river runoff and water supply to urban areas (Fane & Turner, 2010). Recent research has consistently indicated that the primary contributors to the impact on surface water resources are human activities, encompassing factors such as land use changes (Mirhosseini *et al.*, 2018), agricultural irrigation, coal mining, reservoir storage, domestic and industrial water consumption (Luo *et al.*, 2018).

7.4.1 Calculation of water reduction

The SWAT model incorporated meteorological and land use data, spanning from 2004 to 2008 to assess runoff reduction in the Steenkoolspruit basin. The impact of weather (Figure 7-6) and soil and water conservation (Figure 7-7) during the recent period was calculated. Subsequently, the

difference between the simulated and measured runoff values was attributed to change in runoff caused by industrial and domestic water consumption, coal mining, and other influences. Various factors, detailed in Table 7-4, contributed to water reduction in the study area during the recent period.

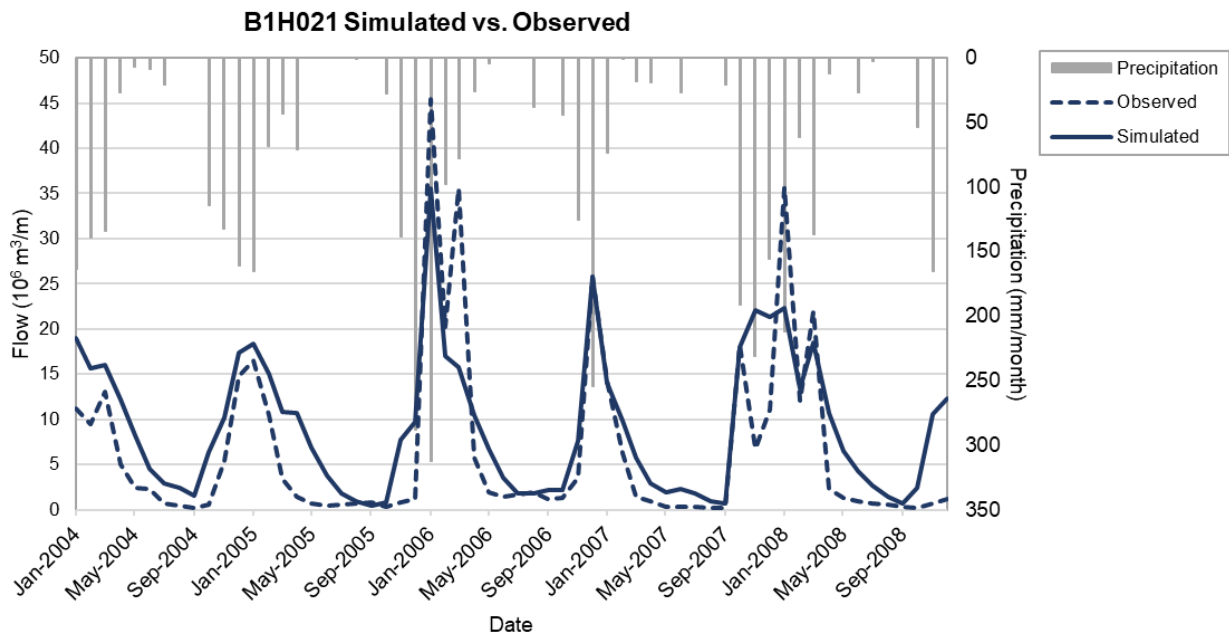


Figure 7-6 Run 2 – Reference period land cover data and recent meteorological data

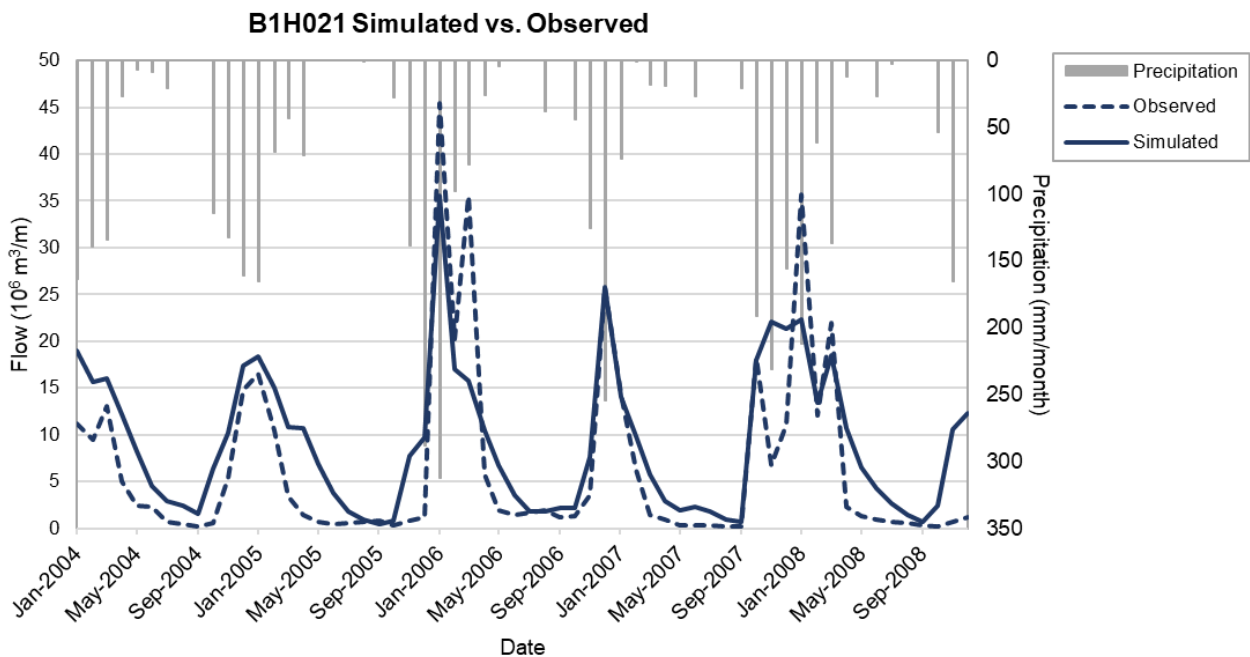


Figure 7-7 Run 3 – Recent period land cover and meteorological data

Figure 7-6 (recent meteorological data) and Figure 7-7 (recent land use data) show similar trends in the calibrated flow. Generally, the simulated base flow is more than the observed base flow. The simulated peak flow was overall more accurate than the base flow.

Table 7-4 Calculations of water reduction in the study area in the recent period (2004–2008)

Unit	Simulated value in reference period	Meteorological data		Land use data		Measured value	Increase in water consumption	Reduction in water from coal mining and other factors
		Simulated value	Water reduction	Simulated value	Water reduction			
10 ⁶ m ³ /m	8.5	7.7	0.9	7.3	0.4	5.6	0.4	1.2
10 ⁶ m ³ /y	102.24	92.02	10.22	87.39	4.63	67.47	5.13	14.79

It was observed that water consumption increased by an average of 5.1×10^6 m³ per year during the recent period (WARMS, 2024). Appendix D displays the volume of water use (m³/m) across various sectors within the quaternary catchment (B11C–B11D). Table 7-4 shows that the reduction in water in the study area was influenced by multiple factors during this period. Specifically, in the recent period (2004–2008) compared to the reference period (1993–1997), Steenkoolspruit experienced an average water reduction of 10.22×10^6 m³ per year due to weather factors – calculated as the simulated value in the reference period subtracted from the meteorological simulated value. Soil and water conservation measures accounted for an average reduction of 4.63×10^6 m³ per year, calculated as the meteorological simulated value subtracted from the land use simulated value. Increased water consumption from commercial, agricultural, and water supply services contributed an average of 5.13×10^6 m³ per year, based on known statistical data (WARMS, 2024). Coal mining and other factors were found responsible for an average reduction of 14.79×10^6 m³ per year, calculated as the land use simulated value subtracted from the measured value, in addition to increased water consumption.

These findings suggest that various factors, including human activities such as coal mining, significantly influence short-term changes in river runoff. It is, however, essential to highlight that natural factor also played a substantial role. Due to the limited availability of primary data, only the main influencing factors were considered. Notably, the coal mining factor encompassed everything except weather, water, and soil conservation, as well as consumption by commercial, agricultural, and water supply services.

7.5 Chapter summary

The manual calibration process aimed at aligning monthly observed and simulated flow data that was statistically unacceptable. Although one of the three model performance criteria (R^2) was successful, the model tended to over-simulate the peak flows. Many other studies that were conducted while using the SWAT model (Govender & Everson, 2005; Qi & Grunwald, 2005; Schuol *et al.*, 2008a) also noted a high sensitivity of the CN2 parameter. Qi and Grunwald (2005) highlighted the influence of land use on the CN number, stating that "the land use determined the CN numbers, which describe the process of infiltration and surface runoff". The high peak flows noted during the model simulation may be attributed by the CN2 values that could not be correctly calibrated. This may not be the only reason for the high peak flows since the manual calibration significantly improved results compared to the initial model but failed to produce acceptable model simulations. The runoff simulation is the result of several different processes and parameters in the SWAT model.

The calibration period of the model demonstrated particularly good results, encompassing the graphical comparison that considered various uncertainties through the SUFI-2 program (P- and R-factor), and quantitative analysis. However, during validation, the results, especially in the quantitative analysis, were poorer. The model, while able to bracket a large portion of observed data in a small uncertainty band, indicated an unacceptable PBIAS during validation (Figure 7-5). The NSE and R^2 results indicated that the model was able to adequately simulate base and peak flows. Moriasi *et al.* (2007) indicated that a negative PBIAS value suggests a model bias towards overestimating flow. The choice of the objective function (in this case the NSE) in SUFI-2 may impact the results (Abbaspour, 2014). Another possibility that could affect the results are the conditions during the validation period that differs from the calibration period, although it is doubtful, given that other evaluation measures (such as R^2) are deemed acceptable. It is advisable to have more rigorous performance evaluations in model calibration than in validation (Moriasi *et al.*, 2007).

The use of NSE as the objective function is common in literature (ASCE Task Committee on Definition of Criteria for Evaluation of Watershed Models of the Watershed Management Committee, Irrigation and Drainage Division, 1993; Moriasi *et al.*, 2007). However, Legates and McCabe (1999) highlighted concerns, stating that NSE tends to overestimate the larger values in a time series while lower values will be neglected. Therefore, efficiency measure NSE focuses more on peaks than low flow predictions (Krause *et al.*, 2005; Qi & Grunwald, 2005). However, despite the concerns, NSE was considered adequate for this study. Considering the manual calibration results (Figure 7-1), the trend appeared a bit higher for the simulated peak flow to a greater degree than the troughs. The emphasis that NSE placed on peak flow could prove beneficial throughout the calibration and validation processes. This focus on correcting peak flows may imply that this was essentially the aspect addressed during model calibration.

In this study, focusing solely on flow station B1H021 at the outflow of the study area was deemed logical. Qi and Grunwald (2005) emphasised the importance of having multiple calibration and validation stations to enhance the adjustment of models such as SWAT to local and regional watershed characteristics. This not only improves predictions for reliable water flow simulations but also increases confidence when predicting different scenarios and flow in ungauged stations. While the input climate data, aside from rainfall, was sourced from a global database in SWAT, posing potential data quality concerns for a small, localised area, the availability of rainfall data for the catchment area outside the study boundary was available. This data, combined with global weather station data, was used for rainfall input.

The limitations of using the SWAT model in a mining catchment in Africa extended to the limited availability of soil and base flow data. Soil parameters for the catchment were estimated, introducing substantial uncertainty and, similarly, the land use parameters were also based on vegetation cover types of Northern America, potentially causing uncertainty in catchment modelling (Dabrowski, 2013). The complexity of mining regions exacerbates the challenge of dealing with the high number of parameters, complicating model parameterisation and calibration of SWAT (Arnold *et al.*, 2012b).

Adjusting certain parameters in the SWAT model revealed a similar runoff distribution for the recent period compared to the reference period. Compared to the reference period, changes in weather caused a reduction of $10.22 \times 10^6 \text{ m}^3$ per year on average in water in the Steenkoolspruit basin, with soil and water conservation measures accounting for a reduction of $4.63 \times 10^6 \text{ m}^3$ per year on average. Conversely, the water consumption of commercial, agricultural and water supply services increased by $5.13 \times 10^6 \text{ m}^3$ per year on average, and coal mining and other factors contributed $14.79 \times 10^6 \text{ m}^3$ per year on average.

The study's overall results demonstrated that the SWAT model, within a sufficiently calibrated parameter range, can reasonably simulate monthly runoff in the catchment. This finding aligns with other research over the world, indicating the SWAT model's capability to produce comparable observed and simulated flow data (Govender & Everson, 2005). However, achieving satisfactory simulations required a careful and time-consuming effort to calibrate specific SWAT model parameters for the study catchment. Similar research in South Africa emphasised the importance of accurate parameterisation for local conditions (Govender & Everson, 2005). While global studies such as that in the Himalayas highlighted the significance of remote sensing techniques and runoff models, adaptations are needed for specific regions of interest (Winiger *et al.*, 2005).

Thoroughly parameterising and adapting the SWAT model to the area of interest would require access to more or higher-quality data. Scarce data remains a significant challenge in hydrological modelling, particularly in Africa (Mango *et al.*, 2011; Schuol *et al.*, 2008a, 2008b). The use of a semi-automated program such as SUFI-2 in SWAT-CUP, considering all forms of uncertainty in the

modelling process, coupled with manual calibration and a thorough understanding of the catchment area's hydrology, could potentially enable adequate modelling. Studies using SUFI-2 procedures have successfully minimised differences between observed and simulated data (Ridwansyah *et al.*, 2014). Applying the SUFI-2 program to calibrate and validate SWAT modelled areas across the whole of Africa was successful, providing quantification of prediction uncertainties (Schuol *et al.*, 2008b).

7.6 Similar findings

The application of the SWAT hydrological model has been extensive both globally and within South Africa. However, one of the foremost challenges encountered by scientists worldwide pertains to limited data availability, particularly concerning hydrological and soil studies. This constraint significantly impacts the effectiveness and reliability of modelling efforts across various geographical regions and research contexts.

Bouslihim (2020) undertook a challenging endeavour by applying a hydrological model, particularly the SWAT model, in the Mazer (Morocco) watershed amid limited data availability. Despite these challenges, the study exhibited commendable model performance during both calibration and validation phases, achieving notable NSE and R^2 values between 0.64 and 0.65. Following calibration, the model parameters were utilised to estimate flow and soil erosion in the ungauged watershed. Despite the modest erosion rates observed, the study advocates for the utilisation of the generated model and results to inform soil management practices and land use decisions in both watersheds. The research highlighted significant limitations, including insufficient runoff data, poor spatial distribution of rainfall stations, and the absence of auxiliary data such as temperature, wind speed, relative humidity, and solar radiation. To address these limitations, the study suggests the need for increased monitoring field data and the installation of additional weather stations to accurately model water resource components within the watershed.

In a similar study Thebe (2023) utilised the SWAT model to simulate water runoff patterns in the Odra River basin (Czech Republic), characterised by its vast scale and climatic diversity. Due to constraints in computing power and processing time, a DEM with a resolution of 90 meters was utilised for model development. While a higher resolution would have been preferable for enhanced accuracy, attempts to utilise finer resolutions were unsuccessful. Nonetheless, the delineated watershed area was deemed satisfactory when compared to the actual area provided by Global Runoff Data Centre (GRDC), despite potential uncertainties arising from the coarse resolution DEM. It's important to note that other gridded datasets for land use and soil type classifications may introduce additional uncertainties. Additionally, the SWAT model used in this study lacked a customised classification database for Europe, necessitating adaptations based on existing literature and guidelines from the COPERNICUS data service. Similarly, adjustments were made to the soil

map obtained from the European Soil Data Centre (ESDAC) to align with the SWAT model's format, incorporating information from previous studies and the data provider. However, these adaptations involved certain assumptions, introducing potential uncertainties. Following model development, calibration and validation were conducted on a daily basis to assess simulation performance, yielding satisfactory results. Despite simplifications in the model setup, such as the exclusion of critical factors like reservoirs and tributaries, the SWAT model effectively simulated overall runoff dynamics and replicated the watershed system, highlighting its versatility and applicability for watershed management.

Perry's (2015) objective was to conduct hydrological modelling in a mountainous region of South Africa, focusing on Mariepskop Mountain, one of Mpumalanga Province's highest peaks. Utilising the SWAT model, monthly runoff values were reasonably simulated after calibration and validation with the SUFI-2 program in SWAT-CUP. Given the region's mountainous terrain, data availability was limited, particularly concerning climate and soil data quality. Although calibration simulations yielded favourable results, validation outcomes were comparatively less satisfactory but still met evaluation criteria standards. Nonetheless, the study suggests that the SWAT model adequately simulated flow and holds potential for application in similar ungauged catchment areas with analogous land use and climate. Future utilisation for scenario analysis and water resource management is feasible, contingent upon careful calibration of base flow data and incorporation of catchment-originated climate data to enhance model accuracy.

Like Bouslihim's and Perry's studies, this study also faced challenges related to model performance, particularly in simulating peak flows. This indicates a common issue in hydrological modelling, where certain parameters, such as CN2, can influence peak flow simulation. Like Perry's study, this study demonstrated better results during calibration compared to validation. This suggests that while the model could fit well during the calibration period, its performance deteriorated during validation, possibly due to different conditions or biases introduced during calibration. This study, along with Bouslihim's and Perry's studies, highlighted the sensitivity of certain parameters in the SWAT model, such as CN numbers, to land use changes. This underscores the importance of accurate parameterization, especially for specific local conditions. Both this study and Perry's noted limitations in data availability, particularly concerning soil data and climate inputs. This is a common challenge in hydrological modelling, especially in regions like Africa where data can be scarce.

While Bouslihim's and Perry's studies focused on simulating runoff in specific catchment areas, this study has a broader focus, including assessing the impact of land use changes and water management practices. Also, this study discussed the impact of model biases and the choice of objective functions, such as NSE, on model performance, which adds depth to the understanding of the modelling process compared to some of the other studies. This study, similar to Perry's study,

provided recommendations for improving model accuracy, such as calibrating base flow data and including local climate data. This suggests a forward-looking approach to addressing model limitations and improving future simulations.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The study area is a unique region characterised by diverse natural processes and human impact, creating a distinctive environment. Prior to the initiation of mining operations around a century ago, the broader Mpumalanga province was unique for its diverse ecosystems, natural beauty, and rich biodiversity. The strategic importance of this study area to the country is underscored by the presence of both natural beauty and industrial development, combined with a blend of abundant geological history and significant coal reserves.

Mining in these coal reserves has not only posed a threat to biodiversity and adversely affected wetlands, but has also significantly altered surface water, exerting considerable pressure on water resources. The impact of the mining industry on water sources in South Africa has reached a critical level.

In the past, the scarcity of clean drinking water did not seem such a huge problem, as water resources were abundant, and climate change, including rainfall variability, was not a concern. The financial income generated by mining companies were prioritised and considered more valuable than the preservation of a natural resource. However, the situation has evolved, and water resources in South Africa are now considered scarce. Increasing water demands in semi-arid South Africa necessitate more efficient management of existing water resources to minimise shortages and public conflicts. In this context, computer simulations can serve as a powerful tool for aiding in water resource planning and decision-making.

Globally, there is a wide variety of hydrological models, each equipped with different built-in capabilities and designed for specific purposes. Nevertheless, selecting the most suitable model for a particular application can be a challenge. This study aimed at effectively managing a watershed impacted by mining activities and the associated water resources. Achieving this goal proved challenging due to the scarcity of accurate and appropriate data. Despite the abundance of information about the watershed, much of it is not publicly accessible, making it more difficult to create a rainfall–runoff model for the study area catchment, particularly given the reduced availability of rainfall and flow monitoring data.

In response to the challenges posed by the complex hydrological dynamics of mining-affected catchment areas, this study incorporated a CSM to enhance the understanding of key hydrological

processes. The CSM serves as a framework for integrating geological, hydrological, and anthropogenic factors, providing a comprehensive overview of the system under study.

The notion of a "mining catchment" encapsulates the unique hydrological challenges and controversies inherent in regions affected by mining activities. These areas experience distinct hydrological processes shaped by mining operations, such as changes in surface water flow patterns, alterations in soil properties, and impacts on groundwater dynamics.

Prior to the development of the rainfall–runoff model, an examination of the hydrological components in the study area and the factors influencing the hydrological model was conducted. This study led to a review of potential models to identify the most suitable one. One of the most important criteria was the ability of the model to effectively simulate hydrological processes, especially in watersheds with limited data availability. The ArcSWAT model was recognised as a suitable model for this research. To accurately represent reality into the model, a DEM was utilised to establish watershed boundaries, delineate sub-basins, and define land use and soil data, while also configuring model parameters. The setup process involved meticulous consideration of input data accuracy and calibration to enhance the reliability of the model for effective watershed management and planning.

The utilisation of the model's built-in database helped in addressing data limitations within the catchment, yet it introduced both advantages and obstacles. While serving as a readily accessible spatial data source, its ability to accurately depict local conditions proved paramount. Discrepancies with the study area could potentially compromise the precision of model outputs, introducing inaccuracies and biases. Therefore, thorough validation and calibration were imperative to evaluate model performance effectively. Augmenting the database with locally sourced data emerged as a strategy to bolster its reliability in capturing the nuances of the watershed.

A detailed analysis was conducted on the monitoring data of the study area, focussing on both precipitation and flow data. Flow station B1H021 and rainfall gauge B1E001 were identified as suitable for the rainfall–runoff model. B1H021, serving as the outflow station for the entire study area, emerged as the most representative. Meanwhile, B1E001 exhibited the highest percentage of consistently reliable data (80.72%). The time series data were further divided into three distinct periods: a reference period, a middle period, and a recent period.

The reference period model was created, manually calibrated, and validated. The manual calibration demonstrated that SWAT-CUP would enhance the robustness of the model, leading to a more comprehensive understanding of hydrological processes in the study area, ultimately increasing confidence in the model's predictions and its utility for water resource management and decision-making.

For the semi-automated calibration using SUFI-2, important parameters such as CN, SOL_K, and RCHRG_DP, were adjusted. Mining activities exert both direct and indirect influences on these parameters, specifically the CN and SOL_K. Direct impacts stem from land disturbance associated with mining, altering land cover, and soil properties. For instance, vegetation removal and soil compaction directly affect the CN, influencing the hydrological response of the landscape. Similarly, mining operations, through excavation and changes in topography, directly impacted soil hydraulic conductivity by modifying soil structure. Indirect impacts manifest through the introduction of contaminants into water sources, altering water quality and subsequently influencing the CN and SOL_K. For example, pollutants can affect soil quality, reducing infiltration rates and altering the hydraulic conductivity of the soil.

The calibration phase of the ArcSWAT model produced positive outcomes, supported by graphical comparisons and quantitative analyses. However, during validation, particularly in quantitative terms, the performance of the model was less than satisfactory, marked by an unacceptable PBIAS. While the model successfully captured a significant portion of observed data within a narrow uncertainty range, the negative PBIAS during validation raised concerns about a bias toward overestimating flow. The selection of NSE as the objective function in the SUFI-2 program could influence results, and discrepancies between calibration and validation periods indicated a necessity for more stringent performance criteria during model calibration.

In spite of reservations regarding the NSE focus on peak flows, it was deemed suitable for this study, particularly considering the emphasis on correcting peak flows observed in manual calibration results. The study focused on a single flow station, B1H021, situated at the outflow of the watershed, while recognising the significance of multiple calibration and validation stations to refine the model. Utilising a worldwide weather database for SWAT input data, along with local rainfall data, addressed potential concerns about data quality.

The limitations encountered in utilising SWAT for a mining-impacted catchment in South Africa, particularly the absence of soil and base flow data leading to uncertainties in parameter estimation, align with findings observed in similar studies within analogous contexts. Existing literature on hydrological modelling in mining-affected areas has consistently highlighted challenges related to data gaps, emphasising the importance of comprehensive datasets for accurate parameterisation. These limitations echo the broader difficulties encountered in applying SWAT models in diverse geographical and environmental settings, shedding light on the need for context-specific solutions and data collection strategies. By drawing parallels with comparable studies, the identified limitations contribute to a growing body of knowledge that underscores the significance of addressing data uncertainties when employing hydrological models in mining-impacted catchments.

The study revealed changes in the water balance caused by various factors such as weather variations, conservation efforts, increased water usage, and influences related to mining. Notably, coal mining and other factors contributed on average $14.79 \times 10^6 \text{ m}^3$ annually, calculated by subtracting the simulated land use value from the measured value, along with an increase in water consumption.

Overall, the findings indicate that the SWAT model can effectively simulate monthly runoff within a properly calibrated parameter range, consistent with global research. Nevertheless, attaining accurate simulations demands meticulous calibration specific to the study catchment, emphasising the significance of accurate parameterisation for local conditions.

Customising the SWAT model to the study area poses a challenge due to the need for increased or improved data quality, a persistent challenge in hydrological modelling, especially in Africa. Enhancing modelling accuracy by reducing discrepancies between observed and simulated data could be achieved through the incorporation of semi-automated tools such as SUFI-2 in SWAT-CUP, combined with manual calibration and a comprehensive understanding of catchment hydrology. The successful utilisation of SUFI-2 procedures in Africa highlights their capability to assess prediction uncertainties in hydrological models.

The potential of the model extends to future scenario analysis and water resource planning and management, albeit an amount of caution would need to be implemented. Calibrating the base flow data generated by the model, along with incorporating climate data from the catchment area, would significantly enhance the accuracy of the model's results.

This project can be seen as an investigative examination into the suitability of employing the SWAT hydrological model to simulate monthly runoff values within a mining impacted catchment area. Consequently, this study has demonstrated the effectiveness of the semi-distributed hydrological model, SWAT, in accurately simulating the runoff in a South African mining impacted catchment area. The overarching aim of the study, to advance knowledge in the field of water resources by comprehensively investigating the impacts of mining on catchments, while concurrently emphasising the significance of effective water resource management, was systematically addressed through specific objectives. First, a numerical rainfall-runoff hydrological model tailored to the mining catchment's specific characteristics was developed. This was achieved by collecting comprehensive data on land use, geology, topography, and hydrological parameters, aligning with the objective of configuring a suitable model. Calibration and validation processes were conducted using observed data to ensure the accuracy and reliability of the hydrological model, fulfilling the aim of accurate representation. Subsequently, the model was refined through iterative improvements to simulate water flow under diverse scenarios, incorporating variations in rainfall, land use, and other relevant factors. This fulfilled the objective of simulating flow within the mining catchment under different

conditions. Finally, the study evaluated the impacts of land use changes and climate variability on hydrological processes by simulating these scenarios. The comprehensive fulfilment of these objectives demonstrated the potential of hydrological modelling as a tool for effective water resource management in mining catchments, aligning with the overarching aim of the study.

8.2 Future scenarios

Water resource managers grapple with a myriad of often conflicting demands and uncertainties arising from climate change, consumer needs, and land use patterns. This complexity poses significant challenges in devising effective water management plans. To address these issues, water managers must discern problems, propose solutions, and recognise opportunities within their water resource management. Modelling emerges as a valuable tool in this context, offering a systematic approach for water managers to identify challenges, assess potential solutions, and seize opportunities. Through modelling, decision-makers gain insights into the environmental and consumer impacts of their proposed actions, facilitating more informed and strategic water resource management decisions (Loucks & Van Beek, 2005).

Hydrological models such as SWAT offer mining and water resource management authorities (Department of Water Affairs) powerful tools for effective drainage area management and scenario prediction. These models enable the simulation of water flow, quality, and land use impacts, facilitating water resource planning and allocation. Mines can assess the consequences of land use changes, predict the impact of climate change, and simulate various scenarios to inform decision-making. SWAT models also contribute to operational decision support by integrating real-time data for continuous monitoring and emergency response planning. Regulatory compliance is enhanced through environmental impact assessments and the development of mitigation strategies. Moreover, these models serve as valuable communication tools, fostering engagement with local communities and regulatory bodies. Overall, the integration of hydrological models into water management strategies empowers mines and the Department of Water Affairs to make informed, sustainable decisions and address environmental challenges in drainage areas.

8.3 Recommendations

The following recommendations represent various viewpoints and perspectives on the project in its entirety:

- The extensive assistance provided to users greatly facilitated the utilisation of the SWAT model. This support encompassed various elements, including GIS interface tools, user support groups dedicated to both the SWAT model and SWAT-CUP program, a SWAT

literature database, web-based documentation, and instructional videos available on the SWAT website.

- Incorporating rainfall data from a distant downstream gauge, such as rain gauge B1E001, introduced limitations in capturing the spatial variability of precipitation within the catchment. This downstream location could have led to underrepresentation or smoothing of rainfall patterns, potentially impacting the accuracy of hydrological modelling results, particularly in areas with significant spatial heterogeneity. However, by carefully accounting for these spatial limitations and integrating complementary data sources, such as satellite-derived precipitation estimates or local rain gauge networks (South African Weather Service), researchers can mitigate these effects and enhance the reliability of the hydrological model.
- To enhance the accuracy of runoff modelling in simulating flow, an increase of available data becomes imperative. The incorporation of more data, particularly observed flow, and rainfall data, would enable the consideration of spatial variability within the modelled catchment areas, leading to more precise parameterisation and calibration.
- Calibrated models of catchment areas offer a valuable means to evaluate potential impacts stemming from ongoing land use changes, potential increases in abstraction, and the influence of climate change on runoff. This proves especially significant in water resource management and planning, particularly in African watersheds where water security remains a critical concern.
- Additionally, calibrated models can be applied to assess water resources in neighbouring ungauged watersheds, provided that conditions such as land use and soil variables are similar.
- Despite the constrained scope of the project and limited datasets, the SWAT model was not used to its full potential in this study. The SWAT model is equipped to simulate sediment loading and diverse agricultural land management practices. Therefore, if relevant data are acquired, there exists substantial potential to leverage this model for various purposes in the B11C–B11E catchment.
- This project offers a comprehensive guide detailing the setup and execution of the SWAT model in this specific catchment, serving as a valuable resource for future research focused on hydrological modelling.
- To mitigate potential biases and uncertainties stemming from the utilisation of the global dataset in ArcSWAT, it is recommended to conduct thorough validation and calibration exercises tailored to the specific characteristics of the South African study area. This entails comparing model outputs against locally observed data and refining model parameters accordingly. Additionally, incorporating locally derived data or customising parameters to better align with regional conditions can enhance the accuracy and reliability of model simulations.

By employing these strategies, the reliability and applicability of ArcSWAT for watershed management in South Africa can be significantly enhanced.

REFERENCE LIST

- Abbas, N., Wasimi, S.A., Al-Ansari, N. & Baby, S.N. 2018. Recent trends and long-range forecasts of water resources of northeast Iraq and climate change adaptation measures. *Water*, 10(11), art. 1562. <https://doi.org/10.3390/w10111562>
- Abbaspour, K.C. 2014. *SWAT-CUP 2012: SWAT calibration and uncertainty programs – A user manual*. Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland. https://swat.tamu.edu/media/114860/usermanual_swatcup.pdf
- Alsilibe, F. & Bene, K. 2022. Watershed subdivision and weather input effect on streamflow simulation using SWAT model. *Pollack Periodica*, 17(1):88–93. <https://doi.org/10.1556/606.2021.00349>
- Andaryani, S., Trolle, D., Nikjoo, M.R., Moghadam, M.H.R. & Mokhtari, D. 2019. Forecasting near-future impacts of land use and climate change on the Zilbier river hydrological regime, northwestern Iran. *Environmental Earth Sciences*, 78, art. 188. <https://doi.org/10.1007/s12665-019-8193-4>
- Arnold, J.G., Srinivasan, R., Muttiah, R.S. & Williams, J.R. 1998. Large area hydrological modelling and assessment Part I: Model development. *Journal of the American Water Resources Association*, 34(1):73-89. <https://doi.org/10.1111/j.1752-1688.1998.tb05961.x>
- Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B. & Neitsch, S.L. 2012a. Soil & water assessment tool: Input/output documentation. Version 2012. Texas Water Research Institute, TR-439. <https://swat.tamu.edu/media/69296/swat-io-documentation-2012.pdf>
- Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensven, A., Van Liew, M.W., Kannan, N. & Jha, M.K. 2012b. SWAT: Model use, calibration and validation. *Transactions of the ASABE*, 55(4):1491-1508. <https://swat.tamu.edu/media/99051/azdezasp.pdf>
- ASCE Task Committee on Definition of Criteria for Evaluation of Watershed Models of the Watershed Management Committee, Irrigation and Drainage Division. 1993. Criteria for evaluation of watershed models. *Journal of Irrigation and Drainage Engineering*, 119(3):429-442. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1993\)119:3\(429\)](https://doi.org/10.1061/(ASCE)0733-9437(1993)119:3(429))

Asl-Rousta, B., Mousavi, S.J. & Ehtiat, M. 2017. Model selection techniques in SWAT-based hydrological modelling. *European Water*, 57(1):347-352.

https://www.ewra.net/ew/pdf/EW_2017_57_45.pdf

Balasubramanian, A. 2017. An overview of Mining Methods.

https://www.researchgate.net/publication/314502989_AN_OVERVIEW_OF_MINING_METHODS

Dat of access: 06 May 2024.

Banks, V.J., Palumbo-Roe, B., Van Tonder, D., Davies, J. and Chevrel, S. 2011. *Conceptual models of Witbank coalfield, South Africa. Earth Observation for Monitoring and Observing Environmental and Societal Impacts of Mineral Resources Exploration and Exploitation, CEC FP7 Project EO-MINERS, Deliverable D3.1-2.*

Beven, K.J. 1989. Changing ideas in hydrology – The case of physically-based models. *Journal of Hydrology*, 105(1-2):157-172. [https://doi.org/10.1016/0022-1694\(89\)90101-7](https://doi.org/10.1016/0022-1694(89)90101-7)

Beven, K.J. & O'Connell, P.E. 1982. *On the role of physically-based distributed modelling in hydrology*. Report no. 81. Institute of Hydrology. https://nora.nerc.ac.uk/5847/1/IH_081.pdf

Bouslihim, Y. 2020. *Hydrological and soil erosion modeling using SWAT model and Pedotransfert Functions: a case study of Settat-Ben Ahmed watersheds, Morocco*. Morocco: Hassan First University. (Thesis – PhD).

Bruwer, P.W. & Khwidzhili, R.H. 2022. The role of private agronomists towards the sustainability of commercial crop farmers in the eastern highveld of Mpumalanga, South Africa. *South African Journal of Agricultural Extension*, 50(1):147-162. <https://doi.org/10.17159/2413-3221/2022/v50n1a11704>

Buchan, I.F., Baars, L.F. & Northcote, C.S. 1980. Opencast coal mining at Kriel Colliery. *Journal of the Southern African Institute of Mining and Metallurgy*, 80(1):48-55.

https://doi.org/10.10520/AJA0038223X_1294

Butler, E. 2019. *Palaeontological desktop assessment of the proposed Kriel Power Station lime plant upgrade, Mpumalanga province*. PGS Heritage. Pretoria, South Africa.

<https://sahris.sahra.org.za/sites/default/files/heritagereports/SE2292-Kriel%20LPU-Appendix%20F2-PIA-Final.pdf>

Cairncross, B. & Dixon, R. 1995. *Minerals of South Africa*. Johannesburg: The Geological Society of South Africa.

Chiumia, S. 2021, July 16. *Coal-affected but also coal-dependent: Mpumalanga, the coal-mining hotspot*. Climate Justice Central. <https://www.climatejusticecentral.org/posts/coal-affected-but-also-coal-dependent-mpumalanga-the-coal-mining-hotspot> Date of access: 20 Feb. 2024.

CGS (Council for Geoscience). 1986. 1:250 000 Geological Map of 2628 East Rand. [https://maps.geoscience.org.za/hosting/rest/services/Hosted/East_Rand_2628_Geology_250K_1986_\(MB\)/FeatureServer](https://maps.geoscience.org.za/hosting/rest/services/Hosted/East_Rand_2628_Geology_250K_1986_(MB)/FeatureServer) Date of access: 10 Jun. 2022.

CGS (Council for Geoscience). 2022. *Active mines*. https://www.geoscience.org.za/wpfd_file/active-mines/ Date of access: 10 Jun. 2022.

Colín-García, G., Palacios-Vélez, E., López-Pérez, A., Bolaños-González, M.A., Flores-Magdaleno, H., Ascencio-Hernández, R. & Canales-Islas, E.I. 2024. Evaluation of the Impact of Climate Change on the Water Balance of the Mixteco River Basin with the SWAT Model. *Hydrology*, 11(4):1-24. <https://doi.org/10.3390/hydrology11040045>

Cox, K.G. 1992. Karoo igneous activity and the early stages of the break-up of Gondwanaland. In: Storey, B.C., Alabaster, T., Parkhurst, R.J., eds. *Magmatism and the causes of continental break-up*. London: Geological Society of London Special Publications. pp. 137-148.

Dabrowski, J. 2013. *Focus on the SWAT model: A reflective manual on using the SWAT model*. CSIR.

Davis-Reddy, C.L. & Vincent, K. 2017. *Climate risk and vulnerability: A handbook for Southern Africa*. 2nd ed. South Africa, Pretoria: CSIR.

Department of Environmental Affairs (South Africa). 2012. *Highveld priority area air quality management plan*. https://screening.environment.gov.za/ScreeningDownloads/DevelopmentZones/HIGHVELD_PRIORITY_AREA_AQMP.pdf Date of access: 12 Jun. 2022.

Department of Water Affairs and Forestry (South Africa). 2006. *Achievements of the river health programme 1994 – 2004: A national perspective on the ecological health of selected South African rivers*. https://www.dws.gov.za/iwqs/rhp/ecomunication/rhp_e_com_sept2006.pdf Date of access: 15 Aug. 2022.

Department of Water and Sanitation (South Africa). 2008. *Hydrological services – Surface water (Data, dams, floods and flows)*. <https://www.dws.gov.za/Hydrology/>

Department of Water and Sanitation (South Africa). 2013. *Groundwater Resource Directed Measures (GRDM)*. Version 2.3.2.

De Klerk, T.C. 2018. An integrated rainfall-runoff water quality model in a mine impacted karst environment. Potchefstroom: North-West University. (Thesis – PhD).

<http://hdl.handle.net/10394/33847>

DEA (Digital Earth Africa). 2020. Open data cube. <https://www.digitalearthfrica.org/node/7> Date of access: 18 Aug. 2023.

Dube, E. & Van der Zaag, P. 2003. Analysing water use patterns for demand management: The case of the city of Masvingo, Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 28(20-27):805-815. <https://doi.org/10.1016/j.pce.2003.08.004>

Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J.S., & Duncan, A.R. 1997. The timing and duration of the Karoo igneous event, southern Gondwana. *Journal of Geophysical Research* 102(B8):18127-18138. <https://doi.org/10.1029/97JB00972>

Emam, A.R., Kappas, M., Linh, N.H.K. & Renchin, T. 2017. Hydrological Modeling and Runoff Mitigation in an Ungauged Basin of Central Vietnam Using SWAT Model. *Hydrology*, 4(1):1-17. <https://doi.org/10.3390/hydrology4010016>

Falkenmark, M. & Chapman, T. 1989. *Comparative hydrology: An ecological approach to land and water resources*. Paris France: UNESCO.

Fane, S. & Turner, A. 2010. Integrated water resource planning in the context of climate uncertainty. *Water Science and Technology: Water Supply*, 10(4):487-494. <https://doi.org/10.2166/ws.2010.120>

FAO (Food and Agriculture Organization). Year *Digital Soil Map of the World* <https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/446ed430-8383-11db-b9b2-000d939bc5d8> Date of access: 8 Oct. 2022.

Faul, K. 2018. *Sustainable water usage in the mining sector through optimisation of collaborative implementation*. Pretoria: University of Pretoria. (Mini-dissertation – LLB). <http://hdl.handle.net/2263/65647>

Follington, I.L., Deeter, R., Share, D. & Moolman, C. 2001. A new underground auger mining system. *The Journal of The South African Institute of Mining and Metallurgy*, 101(1):25-32. https://journals.co.za/doi/epdf/10.10520/AJA0038223X_2685

Fortuna, J., Waterhouse, J., Chapman, P. & Gowan, M. 2021. Applying practical hydrogeology to tailings storage facility design and management. *Mine Water and the Environment*, 40(1):50-62. <https://doi.org/10.1007/s10230-020-00739-x>

Fourie, H. 2021. *Palaeontological impact assessment: Desktop study*. Garsfontein, South Africa: Archaeological Consulting CC.

Garside, K. 2022. *South Africa's mining industry employment by commodity 2021*. <https://www.statista.com/statistics/241420/south-african-mining-key-facts/> Date of access: 23 Jun. 2022.

Getachew, H.E. & Melesse, A.M. 2012. The impact of land use change on the hydrology of the Angereb Watershed, Ethiopia. *International Journal of Water Sciences*, 1(4):1-7. <http://dx.doi.org/10.5772/56266>

Glavan, M. & Pintar, M. 2014. Metrics overview: Strengths, weaknesses, opportunities and threats of catchment modelling with soil and water assessment tool (SWAT) model. In *Water Resource Management and Modeling* edited by P. Nayak. InTechOpen. <https://doi.org/10.5772/34539>

Glenday, J., Gokool, S., Gwapedza, D., Holden, P., Rebelo, A., Tanner, J., Jumbi, F. & Metho, P. 2022. *Critical catchment model intercomparison and model use guidance development*. (Report No. 2927/1/22). Water Research Commission, Gezina. https://www.wrc.org.za/wp-content/uploads/mdocs/2927_Final%20Report.pdf

Goodrich, D.C. 1992. An overview of the USDA-ARS climate change and hydrology program and analysis of model complexity as a function of basin scale. In *Proceedings of a Workshop on Effects of Global Climate Change on Hydrology and Water Resources at Catchment Scale*. Tsukuba: Japan, pp. 233–242.

Gordon, K. 2023. What is strip mining? *The Assay Insights*. <https://www.theassay.com/articles/the-assay-insights/what-is-strip-mining/> Date of access: 06 May 2024.

Govender, M. & Everson, C.S. 2005. Modelling streamflow from two small South African experimental catchments using the SWAT model. *Hydrological Processes*, 19(3):683-692. <https://doi.org/10.1002/hyp.5621>

Hamraoui, L., Bergani, A., Ettoumi, M., Aboulaich, A., Taha, Y., Khalil, A., Neculita, C.M. & Benzaazoua, M. Towards a Circular Economy in the Mining Industry: Possible Solutions for Water Recovery through Advanced Mineral Tailings Dewatering. *Minerals* 2024, 14(319):1-41. <https://doi.org/10.3390/min14030319>

Hu, X., Liu, X. Zhang, S. & Yu, C. 2023. Nitrogen-cycling processes under long-term compound heavy metal(loids) pressure around a gold mine: Stimulation of nitrite reduction. *Elsevier*, 147:571-581. <https://doi.org/10.1016/j.jes.2023.12.027>

- Hughes, D.A. 2004. Three decades of hydrological modelling research in South Africa. *South African Journal of Science*, 100:638-642. <https://core.ac.uk/download/pdf/145032049.pdf>
- Hughes, D., Ashton, P., Görgens, A., Jewitt, G., Schulze, R., Smithers, J., Pegram, G & Dube, R. 2003. South African research in the hydrological sciences: 1999–2002. *South African Journal of Science*, 99:394-397. <https://journals.co.za/doi/pdf/10.10520/EJC97657>
- Hussainzada, W. & Lee, H.S. 2021. Hydrological Modelling for Water Resource Management in a Semi-Arid Mountainous Region Using the Soil and Water Assessment Tool: A Case Study in Northern Afghanistan. *Hydrology*, 8(1):1-20. <https://doi.org/10.3390/hydrology8010016>
- IISD (International Institute of Sustainable Development). 2015. *WEF Report Identifies Climate Issues as a Top Global Risk*. <https://sdg.iisd.org/news/wef-report-identifies-climate-issues-as-a-top-global-risk/> Date of access: 12 Jun. 2022.
- Janjić, J. & Tadić, L. 2023. Fields of application of SWAT hydrological model – A review. *Earth*, 4(2):331–344. <https://doi.org/10.3390/earth4020018>
- Jhariya, D.C., Khan, R. & Thakur, G.S. 2016. Impact of mining activity on water resource: An overview study. Conference: *National seminar on recent practices and innovations in mining industry* at Raipur, pp. 271-277.
- Johnson, M.R., Van Vuuren, C.J., Visser, J.N.J., Cole, D.I., De V. Wickens, H., Christie, A.D.M., Roberts, D.L., & Brandl, G. 2006. Sedimentary rocks of the Karoo Supergroup. In: Johnson, M.R., Anhaeusser, C.R. & Thomas, R.J., eds. *The geology of South Africa*. Marshalltown: Geological Society of South Africa, pp. 461-499.
- Jurd, R.G. 1977. Longwall mining, with particular reference to its implementation in South African collieries. *The Journal of The South African Institute of Mining and Metallurgy*, 78(3):63-72.
- Kalogiannidis, S., Kalfas, D., Giannarakis, G. & Paschalidou, M. Integration of Water Resources Management Strategies in Land Use Planning towards Environmental Conservation. *Sustainability*, 15(21):1-20. <https://doi.org/10.3390/su152115242>
- Karmakar, H.N. & Das, P.K. 2012. Impact of Mining on Ground and Surface Water. *4th International Mineral Water Association Congress*. https://www.imwa.info/docs/imwa_1991/IMWA1991_Karmakar_187.pdf
- Kalule-Sabiti, M. & Heath R. 2008. Underground water – a key resource – and the associated environmental issues in North-West Province of South Africa. *WISA Biennial Conference*, Sun City, 18-22 May. <http://www.ewisa.co.za/misc/WISACConf/default2008.htm>.

- Keller, A.A., Garner, K., Rao, N., Knipping, E. & Thomas, J. 2023. Hydrological models for climate-based assessments at the watershed scale: A critical review of existing hydrologic and water quality models. *Elsevier*, 867(2023):1-10. <https://doi.org/10.1016/j.scitotenv.2022.161209>
- Krause, P., Boyle, D.P. & Bäse, F. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences*, 5:89-97. <https://doi.org/10.5194/adgeo-5-89-2005>
- Lakshman, S. 2024. *More Critical Minerals Mining Could Strain Water Supplies in Stressed Regions*. World Resource Institute. <https://www.wri.org/insights/critical-minerals-mining-water-impacts> Date of access: 06 May 2024.
- Lee, F.T. & Abel, J.F. Jnr. 1983. Subsidence from Underground Mining Environmental Analysis and Planning Considerations. *U.S. Geological Survey*, 876:1-28. <https://doi.org/10.3133/cir876>
- Legates, D.R. & McCabe, G.J., Jr. 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, 35(1):233-241. <https://doi.org/10.1029/1998WR900018>
- Lisetskii, F.N. & Buryak, Z.A. 2023. Runoff of Water and Its Quality under the Combined Impact of Agricultural Activities and Urban Development in a Small River Basin. *Water* 2023, 15(2443):1-29. <https://doi.org/10.3390/w15132443>
- Loucks, D.P. & Van Beek, E. 2005. *Water resources systems planning and management. An introduction to methods, models and applications*. Turin: UNESCO.
- Luo, Z., Zuo, Q., Gan, R. & Ma, J. 2018. Effect of human activity intensity on stream structure and connectivity in Shaying River Basin, China. *Water Science and Technology: Water Supply*, 18(3):754-766. <https://doi.org/10.2166/ws.2017.122>
- Macfarlane, D. & Bredin, I. 2017. *Buffer zone guidelines for wetlands, rivers and estuaries. Part 2: Practical guide*. WRC Report No. TT 715/2/17. South Africa: Water Research Commission.
- Malley, Z.J.U., Taeb, M., Matsumoto, T. & Takeya, H. 2009. Environmental sustainability and water availability: Analyses of the scarcity and improvement opportunities in the Usangu plain, Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C*, 34(1-2):3-13. <https://doi.org/10.1016/j.pce.2008.02.034>
- Mango, L.M., Melesse, A.M., McClain, M.E., Gann, D. & Setegn, S.G. 2011. Land use and climate change impacts on the hydrology of the Upper Mara River Basin, Kenya: results of a modelling study to support better resource management. *Hydrology and Earth System Sciences*, 15(7):2245-2258. <https://doi.org/10.5194/hess-15-2245-2011>

- Mann, J. & Carr, R. 2023. *Msobo Coal: Mining in majestic Mpumalanga*. Mining Outlook. <https://www.mining-outlook.com/commodities/coal-mining-sector/msobo-coal-mining-in-majestic-mpumalanga> Date of access: 28 Oct. 2023.
- McCarthy, T.S. 2011. The impact of acid mine drainage in South Africa. *South African Journal of Science*, 107(5-6), Art. 712. <https://doi.org/10.4102/sajs.v107i5/6.712>
- Meißner, S. 2021. The impact of metal mining on global water stress and regional carrying capacities– A GIS-based water impact assessment. *Resources*, 10(12), art. 120. <https://doi.org/10.3390/resources10120120>
- Middleton, B.J. & Bailey, A.K. 2011. *Water resources of South Africa, 2-0-05 Study (WR2005). User's guide, Version 2*. (WRC report number TT 513/11) Pretoria: Water Research Commission. <https://www.wrc.org.za/wp-content/uploads/mdocs/TT%20513-11.pdf>
- Minerals Council South Africa, 2022. *The Coal Mining Life Cycle*. Mining for Schools. <https://www.miningforschools.co.za/lets-explore/coal/the-coal-mining-life-cycle> Date of access: 06 May 2024.
- Mirhosseini, M., Farshchi, P., Noroozi, A.A., Shariat, M. & Aalesheikh, A.A. 2018. An investigation on the effect of land use land cover changes on surface water quantity. *Water Supply*, 18(2):490-503. <https://doi.org/10.2166/ws.2017.107>
- Mondal, S., Bandayopahyay, J. & Chakarvarty, D. 2014. Scientific investigation of the environmental impact of mines using geospatial techniques over a small part of Keonjhar district of Orissa. *International Journal of Scientific and Research Publications*, 4(1):1-8. <http://www.ijsrp.org/research-paper-0114.php?rp=P252128>
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. & Veith, T.L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3):885-900. <https://doi.org/10.13031/2013.23153>
- Munnik, V. 2016. *How coal mining in Mpumalanga threatens food security*. GSA Grain. <https://www.grainsa.co.za/how-coal-mining-in-mpumalanga-threatens-food-security> Date of access: 28 Oct. 2023.
- Gonah, T. 2016. Impact of Acid Mine Drainage on Water Resources in South Africa. In: Mujuru, M. & Mutanga, S., (eds.) *Management and Mitigation of Acid Mine Drainage in South Africa*. Pretoria: Africa Institute of South Africa. pp. 41-65.

Ncube, M. 2006. *The impact of land cover and land use on the hydrologic response in the Olifants*. Johannesburg: University of the Witwatersrand (Dissertation – MSc (Eng)).

<http://hdl.handle.net/10539/5799>

North West Province State of the Environment Report. 2002. *North West Province: Environment Outlook: A report on the state of the environment*. Mmabatho, South Africa.

https://soer.environment.gov.za/soer/UploadLibraryImages/UploadDocuments/220218121119_North West full document jX1J3.pdf

Olsson, G. 2013. Water, energy and food interactions – Challenges and opportunities. *Frontiers of Environmental Science & Engineering*, 7(5):787-793. <https://doi.org/10.1007/s11783-013-0526-z>

Oosthuizen, C.C. 2005. Bord and pillar applications on the platinum mine: T-cut mining method. *The Journal of The South African Institute of Mining and Metallurgy*, 105(3):187-192.

Perry, K.A. 2014. *Application of the SWAT hydrological model in a small, mountainous catchment in South Africa*. Pretoria: University of Pretoria. (Dissertation – MSc).

<http://hdl.handle.net/2263/46217>

Pitman, W.V., Kakebeeke, J.P. & Bailey, A.K. 2008. *WRSM 2000 (Enhanced). Water resources simulation model for Windows: User's guide*. Department of Water Affairs and Forestry, Pretoria.

Pitman, W.V. 2011. Overview of water resource assessment in South Africa: Current state and future challenges. *Water SA*, 37(5):659–664. <https://doi.org/10.4314/wsa.v37i5.3>

Qi, C. & Grunwald, S. 2005. GIS-based hydrological modelling in the Sandusky watershed using SWAT. *Transaction of the ASAE, American Society of Agricultural Engineers*, 48(1):169-180.

<https://doi.org/10.13031/2013.17960>

Querner, E.P. & Van Zanen, M. 2013. *Modelling water quantity and quality using SWAT: A case study in the Limpopo River basin, South Africa*. Alterra Wageningen UR.

<https://www.researchgate.net/publication/283418112> Modelling water quantity and quality using SWAT a case study in the Limpopo River basin South Africa

Rabie, A. 1996. Integrated water and land management in South Africa. *SA Public Law*, 11(2):321-354. https://hdl.handle.net/10520/AJA02586568_54

Rafundisani, M. 2018. *EMP consolidation for Thubelisha, Trichardsfontein and Vaalkop mining area: Consolidated surface water assessment report*. Project no. SAS3869. Randburg, South Africa: Digby Wells Environmental.

[https://sahris.sahra.org.za/sites/default/files/additionaldocs/SAS3869 Surface Water Report 2018-01-24 KG Final Compressed.pdf](https://sahris.sahra.org.za/sites/default/files/additionaldocs/SAS3869%20Surface%20Water%20Report%2018-01-24%20KG%20Final%20Compressed.pdf)

Rahm, D., Swatuk, L. & Matheny, E. 2006. Water resource management in Botswana: Balancing sustainability and economic development. *Environment, Development and Sustainability*, 8:157-183. <https://doi.org/10.1007/s10668-005-2491-6>

Ridwansyah, I., Pawitan, H., Sinukaban, N. & Hidayat, Y. 2014. Watershed modelling with ArcSWAT and SUFI2 in Cisadane catchment area: Calibration and validation to prediction of river flow. *International Journal of Science and Engineering*, 6(2):12-21. <https://doi.org/10.12777/ijse.6.2.92-101>

Rossman, L.A. 2010. *Storm water management model. User's manual version 5.1* Cincinnati, OH: United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2019-02/documents/epaswmm5_1_manual_master_8-2-15.pdf

Sakhaee, F. 2021. Hydrological simulation of Silver Creek Watershed using Soil and Water Assessment Tool (SWAT). *Research International Journal of Energy & Environmental Sciences*, 2(1):001-008. <https://msdpublications.com/uploads/article/RIJEES-02-1006.pdf>

Schmeier, S., Hartog, J., Kortlandt, J., Meijer, K., Meurs, E., Sasse, R. & Ter Horst, R. 2019. Water scarcity and conflict: Not such a straightforward link. *Great Insights*. <https://ecdpm.org/work/the-complex-link-between-climate-change-and-conflict-volume-8-issue-4-autumn-2019/water-scarcity-and-conflict-not-such-a-straightforward-link> Date of access: 20 Jan. 2023.

Schröter, D., Cramer, W., Rik, L., Prentice, I.C., Araujo, M.B., Arnell, N.W., ... Zierl, B. 2005. Ecosystem service supply and vulnerability to global change in Europe. *Science*, 310(5752):1333-1337. <https://doi.org/10.1126/science.1115233>

Schuol, J., Abbaspour, K.C., Srinivasan, R. & Yang, H. 2008a. Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model. *Journal of Hydrology*, 352(1-2):30-49. <https://doi.org/10.1016/j.jhydrol.2007.12.025>

Schuol, J., Abbaspour, K.C., Yang, H., Srinivasan, R., & Zehnder, A.J.B. 2008b. Modelling blue and green water availability in Africa. *Water Resources Research*, 44(W07406). <https://doi.org/10.1029/2007WR006609>

Simpson, G.B., Badenhorst, J., Jewitt, G.P.W., Berchner, M., & Davies, E. 2019. Competition for Land: The Water-Energy-Food Nexus and Coal Mining in Mpumalanga Province, South Africa. *Frontiers in Environmental Science*, 7, Art. 86. <https://doi.org/10.3389/fenvs.2019.00086>

Singo, L.R. 2018. *Application of GIS and remote sensing techniques to evaluate the impact of land cover and land use change on the hydrology and water resources of Luvuvhu river catchment in Limpopo Province, South Africa*. Limpopo: University of Venda. (Thesis – PhD).

<http://hdl.handle.net/11602/1215>

South African National Biodiversity Institute. *National Vegetation Map Project (VEGMAP)*

<https://bgis.sanbi.org/Projects/Detail/185> Date of access: 12 Jun. 2023.

Sumi, L. and Thomsen, S. 2001. *Mining in Remote Areas, Issues and Impacts*. MiningWatch Canada/ Mines Alert. https://miningwatch.ca/sites/default/files/mine_impacts_kit_1.pdf Date of access: 4 Jan. 2023.

Svensen, H., Corfu, F., Polteau, S., Hammer, Hammer, Ø. & Planke, S. 2012. Rapid magma emplacement in the Karoo large igneous province. *Earth and Planetary Science Letters*, 325-326:1-9. <https://doi.org/10.1016/j.epsl.2012.01.015>

SWAT User Group. <https://groups.google.com/g/swatuser> Date of access: 15 February 2023.

Taleb, I., Serhani, M.A., Bouhaddioui, C. & Dssouli, R. 2021. Big data quality framework: A holistic approach to continuous quality management. *Journal of Big Data*, 8, art. 76.

<https://doi.org/10.1186/s40537-021-00468-0>

Tang, F.F., Xu, H.S. & Xu, Z.X. 2012. Model calibration and uncertainty analysis for runoff in the Chao River Basin using sequential uncertainty fitting. *Procedia Environmental Sciences*, 13(2012):1760-1770. <https://doi.org/10.1016/j.proenv.2012.01.170>

Thompson, S.A. 1999. *Hydrology for water management*. Rotterdam: A.A. Balkema.

<https://doi.org/10.1201/9780203751435>

Tomiyama, S & Igarashi, T. 2022. The potential threat of mine drainage to groundwater resources. *ScienceDirect*, 27:1-12. <https://doi.org/10.1016/j.coesh.2022.100347>

Ugya, A.Y., Ajibade, F.O. & Ajibade, T.F. 2018. Water Pollution Resulting from Mining Activity: An Overview. Conference: *Proceedings of the 2018 Annual Conference of the School of Engineering & Engineering Technology (SEET)* at FUTA, pp. 703-718.

Uhlenbrook, S., McDonnell, J. & Leibundgut, C. 2003. Preface: Runoff generation and implications for river basin modelling. Special issue. *Hydrological Processes*, 17:197-198.

<https://doi.org/10.1002/hyp.1118>

United Nations Environmental Programme (UNEP). 2012. Status Report on The Application of Integrated Approaches to Water Resources Management.
https://www.unwater.org/sites/default/files/app/uploads/2017/05/UNW_status_report_Rio2012.pdf
Date of access: 09 May 2024.

United States Agency for International Development (USAID). 2021. Water Resource Management. *Water and Development Technical Series*.
<https://www.globalwaters.org/sites/default/files/usaidthatwaterwrmtb115083.pdf> Date of access: 09 May 2024.

USDA & NRCS (United States Department of Agriculture & Natural Resources Conservation Service). 2007. Hydrologic soil groups. In: *Part 630 Hydrology: National Engineering Handbook*. Washington, DC. <https://directives.sc.egov.usda.gov/22526.wba> Date of access: 25 June 2023.

United States Geological Survey. 2022. *United States Geological Survey*.
<https://earthexplorer.usgs.gov/> Date of access: 15 Aug. 2022.

Vitousek, P.M. 1994. Beyond global warming: Ecology and global change. *Ecology*, 75(7):1861-1876. <https://doi.org/10.2307/1941591>

Water Resources of South Africa. 2012. <https://waterresourceswr2012.co.za/resource-centre/> Date of access: 15 Aug. 2022.

WARMS (Water Use Authorization & Registration Management System). South Africa's Water Resources. WARMS – Water Resources of South Africa. <https://www.warms.org.za/> Date of access: 17 Jan. 2024.

Weather, H.S. 2007. Modelling hydrological processes in arid and semi-arid areas: An introduction. In: Weather, H., Sorooshian, S. & Sharma, K.D. (eds.), *Hydrological modelling in arid and semi-arid areas*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511535734.002>

Weatherbase. 2016. Long-term average temperature graph for Kriel, South Africa. In *Weatherbase*. <https://www.weatherbase.com/weather/weather.php3?s=604951&cityname=Kriel-South-Africa> (Accessed 8 November 2023).

Winchell, M.F., Peranginangin, N., Srinivasan, R. & Chen, W. 2017. Soil and water assessment tool model predictions of annual maximum pesticide concentrations in high vulnerability watersheds. *Integrated Environmental Assessment and Management*, 14(3):358-368.
<https://doi.org/10.1002/ieam.2014>

Winiger, M., Gumpert, M. & Yamout, H. 2005. Karakorum–Hindukush–western Himalaya: Assessing high altitude water resources. *Hydrological Processes*, 19(12):2329-2338. <https://doi.org/10.1002/hyp.5887>

Wolkersdorfer, C. & Mugova, E. 2022. Effects of Mining on Surface Water. *Elsevier*, 4(2): 170-188. <https://doi.org/10.1016/B978-0-12-819166-8.00036-0>

Xie, K., Liu, P., Zhang, J., Libera, D.A., Wang, G., Li, Z. & Wang, D. 2020. Verification of a new spatial distribution function of soil water storage capacity using conceptual and SWAT models. *Journal of Hydrologic Engineering*, 25(3):1-17. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001887](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001887)

Xu, C.Y. & Singh, V.P. 1998. A review on monthly water balance models for water resources investigations. *Water Resource Management*, 12:20-50. <https://doi.org/10.1023/A:1007916816469>

Zhang, W., Zhang, J., Yang, N. & Duan, L. 2024. Influence of mining activities on hydrological processes in the mining district, Loess Plateau: insights from spatio-temporal variations of δD and $\delta^{18}O$. *Frontiers in Environmental Science*, 12:1-11. <https://doi.org/10.3389/fenvs.2024.1388262>

APPENDIX A

SWAT INTERFACE COMPONENTS

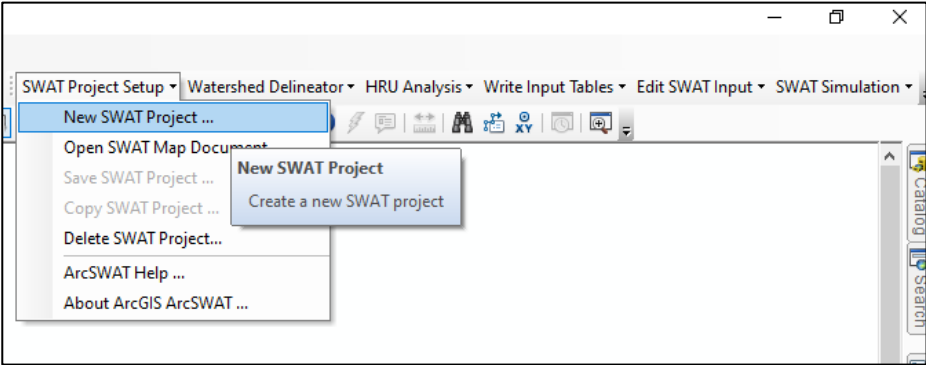


Figure 1: Toolbar at the forefront of the ArcSWAT program interface.

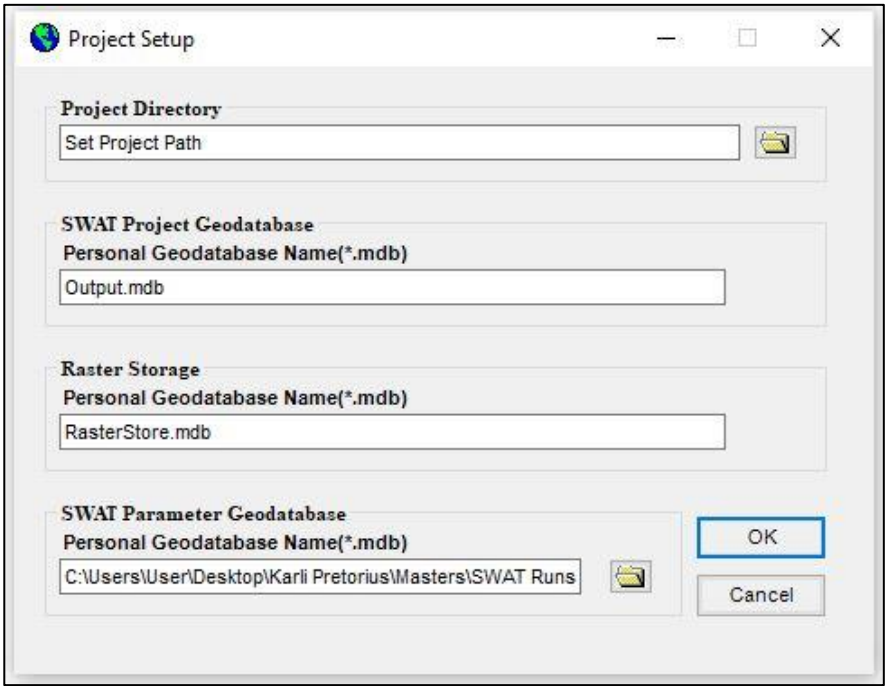


Figure 2: Menu for setting up the project in the ArcSWAT program.

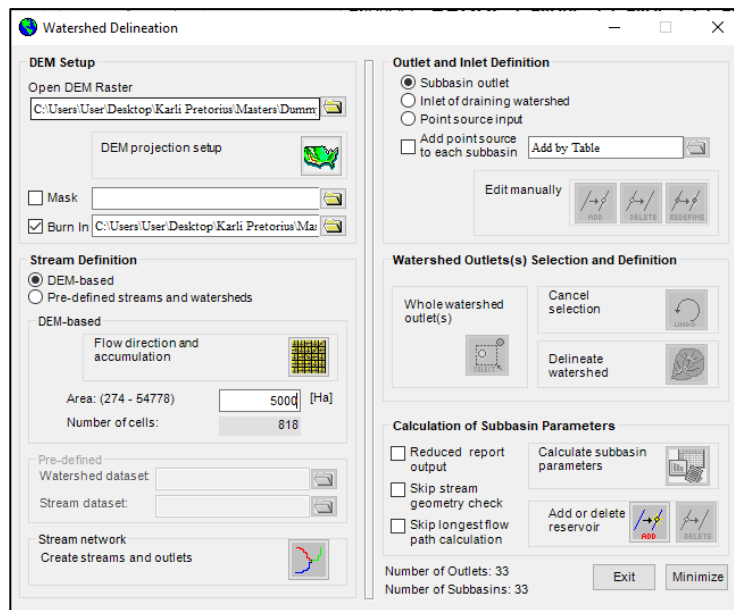


Figure 3: The ArcSWAT program includes a menu for delineating watersheds, which is used to establish quaternary catchments within the study area.

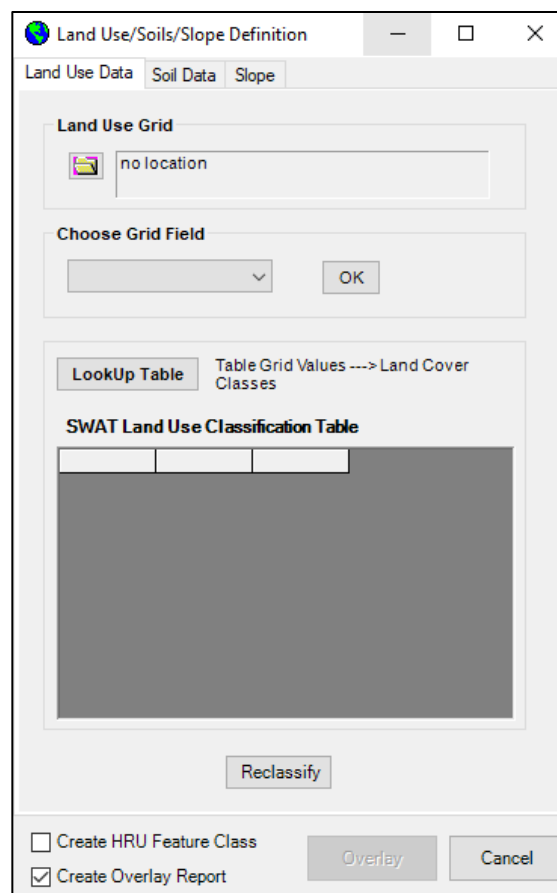


Figure 4: The ArcSWAT menu for overlaying land use, soil, and slope.

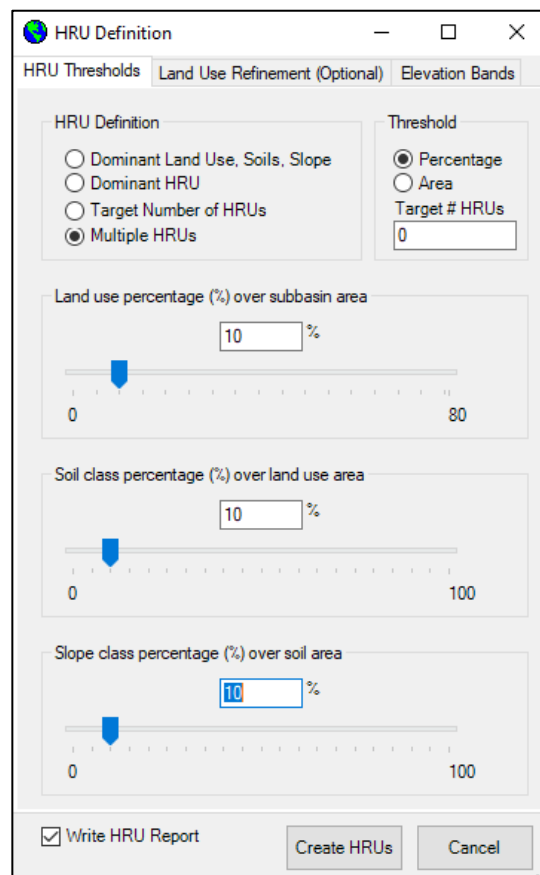


Figure 5: Menu for defining Hydrologic Response Unit (HRU) in ArcSWAT.

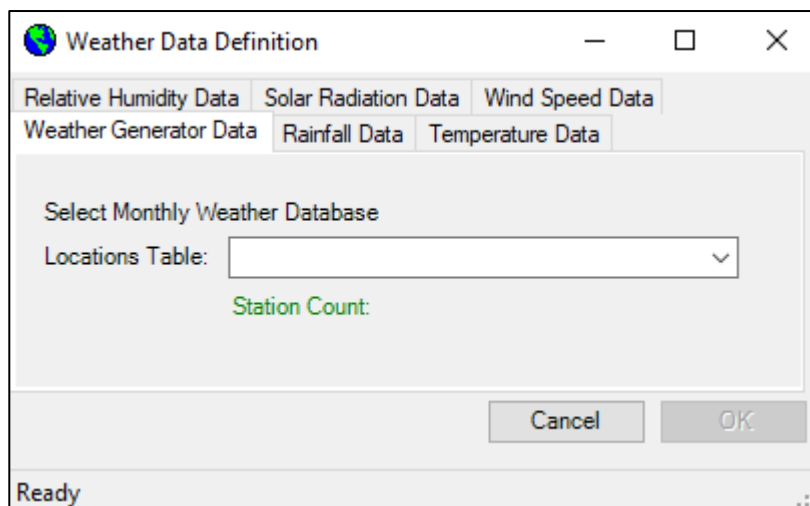


Figure 6: ArcSWAT's menu for defining weather data.



Figure 7: Menu in the ArcSWAT program that allows the program to generate all input tables required for running the SWAT model.

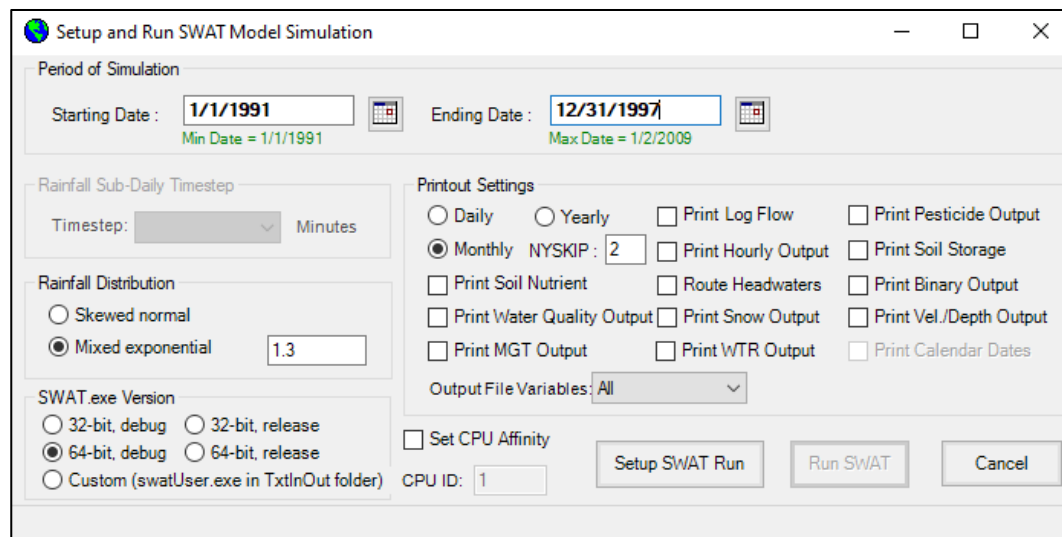


Figure 8: The configuration menu for initiating the SWAT model within ArcSWAT.

APPENDIX B

WATERSHED TOPOGRAPHY REPORT

Elevation report for the watershed 1/1/0001 1:11:25 PM 1/3/2024 12:00:00 AM

Statistics: All elevations reported in meters

Min. Elevation: 1519
Max. Elevation: 1698
Mean. Elevation: 1605.17431619951
Std. Deviation: 31.0950919607773

Elevation	% Area Below Elevation	% Area Watershed
1519	0	0
1520	.02	.02
1522	.03	0
1523	.04	.01
1524	.08	.04
1525	.11	.04
1526	.15	.03
1527	.18	.03
1528	.22	.05
1529	.33	.1
1530	.41	.09
1531	.5	.08
1532	.53	.04
1533	.59	.06
1534	.74	.14
1535	.86	.13
1536	.97	.11
1537	1.15	.18
1538	1.31	.16
1539	1.59	.28
1540	1.93	.34
1541	2.13	.2
1542	2.32	.19
1543	2.53	.22
1544	2.84	.31
1545	3.21	.37
1546	3.37	.16
1547	3.58	.21
1548	3.82	.25
1549	4.18	.36

1550	4.49	.31
1551	4.78	.29
1552	5.06	.28
1553	5.37	.31
1554	5.88	.51
1555	6.41	.53
1556	6.79	.38
1557	7.19	.4
1558	7.57	.38
1559	8.15	.58
1560	8.69	.54
1561	9.12	.44
1562	9.6	.47
1563	10.1	.5
1564	10.66	.56
1565	11.35	.69
1566	11.97	.62
1567	12.51	.54
1568	13.01	.5
1569	13.84	.83
1570	14.65	.8
1571	15.19	.55
1572	15.78	.59
1573	16.4	.61
1574	17.24	.84
1575	18.22	.98
1576	18.96	.74
1577	19.63	.67
1578	20.36	.73
1579	21.37	1
1580	22.46	1.09
1581	23.29	.83
1582	24.2	.91
1583	25.01	.82
1584	26.21	1.19
1585	27.47	1.26
1586	28.4	.93
1587	29.2	.8
1588	30.08	.88
1589	31.17	1.09
1590	32.29	1.13
1591	33.13	.84
1592	34.08	.95
1593	34.91	.83
1594	36.29	1.38
1595	37.64	1.35
1596	38.69	1.05
1597	39.63	.94
1598	40.78	1.15
1599	42.19	1.41
1600	43.78	1.59
1601	44.72	.94
1602	45.63	.91
1603	46.68	1.05
1604	48.2	1.53

1605	49.76	1.56
1606	50.8	1.03
1607	51.83	1.04
1608	52.95	1.11
1609	54.42	1.47
1610	55.87	1.45
1611	56.97	1.11
1612	58.01	1.04
1613	59.05	1.04
1614	60.52	1.47
1615	61.97	1.45
1616	63.04	1.07
1617	63.97	.93
1618	65.05	1.08
1619	66.34	1.29
1620	67.61	1.27
1621	68.66	1.06
1622	69.57	.91
1623	70.54	.96
1624	71.78	1.24
1625	73.09	1.31
1626	73.95	.86
1627	74.75	.8
1628	75.72	.97
1629	76.9	1.18
1630	78.11	1.22
1631	79.04	.93
1632	79.85	.8
1633	80.59	.75
1634	81.65	1.06
1635	82.5	.85
1636	83.27	.77
1637	84.04	.77
1638	84.74	.69
1639	85.51	.77
1640	86.37	.86
1641	87.07	.71
1642	87.73	.66
1643	88.39	.66
1644	89.16	.77
1645	89.99	.83
1646	90.64	.65
1647	91.13	.49
1648	91.66	.53
1649	92.28	.62
1650	92.86	.58
1651	93.37	.51
1652	93.75	.38
1653	94.21	.46
1654	94.81	.6
1655	95.29	.48
1656	95.68	.39
1657	95.94	.25
1658	96.24	.3
1659	96.7	.46

1660	97.02	.32
1661	97.21	.19
1662	97.42	.2
1663	97.66	.25
1664	97.94	.28
1665	98.17	.23
1666	98.36	.19
1667	98.49	.13
1668	98.62	.14
1669	98.78	.16
1670	98.92	.14
1671	99.03	.11
1672	99.09	.06
1673	99.2	.11
1674	99.33	.13
1675	99.4	.07
1676	99.47	.07
1677	99.52	.05
1678	99.56	.05
1679	99.6	.04
1680	99.67	.07
1681	99.71	.04
1682	99.76	.05
1683	99.79	.03
1684	99.86	.07
1685	99.86	.01
1686	99.89	.02
1687	99.89	.01
1689	99.9	0
1690	99.92	.02
1691	99.93	.01
1693	99.94	.01
1694	99.95	.01
1695	99.97	.01
1696	99.98	.02
1697	100	.01
1698	100	0

Subbasin # 1

Statistics: All elevations reported in meters

Min. Elevation: 1519
 Max. Elevation: 1609
 Mean. Elevation: 1554.33753943218
 Std. Deviation: 23.044596505551

Elevation	% Area Below Elevation	% Area Subbasin
1519	.32	.32
1520	1.58	1.26

1522	1.89	.32
1523	2.84	.95
1524	5.68	2.84
1525	8.52	2.84
1526	10.73	2.21
1527	12.3	1.58
1528	14.83	2.52
1529	18.3	3.47
1530	20.5	2.21
1531	22.4	1.89
1532	23.03	.63
1533	23.97	.95
1534	26.81	2.84
1535	28.71	1.89
1536	29.65	.95
1537	31.55	1.89
1538	32.18	.63
1539	33.75	1.58
1540	35.96	2.21
1541	37.22	1.26
1542	38.17	.95
1543	39.12	.95
1544	40.38	1.26
1545	41.64	1.26
1546	42.59	.95
1547	43.85	1.26
1548	44.79	.95
1549	46.06	1.26
1550	47.32	1.26
1551	49.53	2.21
1552	51.1	1.58
1553	51.74	.63
1554	52.68	.95
1555	54.26	1.58
1556	55.84	1.58
1557	57.41	1.58
1558	58.36	.95
1559	59.94	1.58
1560	61.2	1.26
1561	62.78	1.58
1562	63.72	.95
1563	65.3	1.58
1564	66.56	1.26
1565	67.82	1.26
1566	69.72	1.89
1567	70.35	.63
1568	70.66	.32
1569	71.92	1.26
1570	73.5	1.58
1571	74.13	.63
1572	75.08	.95
1573	76.97	1.89
1574	79.18	2.21
1575	80.76	1.58
1576	81.39	.63

1578	82.65	1.26
1579	85.17	2.52
1580	86.12	.95
1582	86.75	.63
1584	88.01	1.26
1585	88.33	.32
1586	88.64	.32
1587	89.27	.63
1588	90.54	1.26
1589	91.17	.63
1590	91.48	.32
1591	91.8	.32
1592	92.11	.32
1594	93.06	.95
1595	94.32	1.26
1596	94.95	.63
1597	95.27	.32
1598	95.9	.63
1600	96.53	.63
1601	96.85	.32
1602	98.42	1.58
1603	98.74	.32
1604	99.37	.63
1606	99.68	.32
1609	100	.32

Subbasin # 2

Statistics: All elevations reported in meters

Min. Elevation: 1536
 Max. Elevation: 1635
 Mean. Elevation: 1589.96996996997
 Std. Deviation: 20.1442190154786

Elevation	% Area Below Elevation	% Area Subbasin
1536	.04	.04
1538	.15	.11
1539	.75	.6
1540	1.31	.56
1541	1.61	.3
1542	1.8	.19
1543	1.95	.15
1544	2.06	.11
1545	2.4	.34
1546	2.48	.08
1547	2.67	.19
1548	2.78	.11
1549	3.19	.41
1550	3.42	.23
1551	3.72	.3
1552	3.94	.23

1553	4.2	.26
1554	4.69	.49
1555	5.03	.34
1556	5.26	.23
1557	5.52	.26
1558	6.01	.49
1559	6.23	.23
1560	6.64	.41
1561	7.02	.38
1562	7.92	.9
1563	9.16	1.24
1564	10.4	1.24
1565	11.9	1.5
1566	12.95	1.05
1567	14.11	1.16
1568	15.2	1.09
1569	17.34	2.14
1570	18.99	1.65
1571	20.2	1.2
1572	21.51	1.31
1573	22.45	.94
1574	24.4	1.95
1575	26.31	1.91
1576	27.4	1.09
1577	29.05	1.65
1578	30.93	1.88
1579	32.62	1.69
1580	34.72	2.1
1581	35.85	1.13
1582	37.01	1.16
1583	38.14	1.13
1584	40.43	2.29
1585	42.3	1.88
1586	43.58	1.28
1587	44.37	.79
1588	45.57	1.2
1589	47.45	1.88
1590	48.72	1.28
1591	50.15	1.43
1592	51.43	1.28
1593	52.82	1.39
1594	54.2	1.39
1595	56.19	1.99
1596	57.58	1.39
1597	58.97	1.39
1598	60.7	1.73
1599	63.29	2.59
1600	65.92	2.63
1601	67.38	1.46
1602	68.36	.98
1603	69.97	1.61
1604	71.92	1.95
1605	74.17	2.25
1606	75.3	1.13
1607	77.18	1.88

1608	78.64	1.46
1609	80.78	2.14
1610	82.7	1.91
1611	84.08	1.39
1612	84.91	.83
1613	86.22	1.31
1614	88.63	2.4
1615	90.92	2.29
1616	92.42	1.5
1617	93.36	.94
1618	94.18	.83
1619	95.23	1.05
1620	95.91	.68
1621	96.4	.49
1622	96.77	.38
1623	97.3	.53
1624	98.01	.71
1625	98.65	.64
1626	98.95	.3
1627	99.1	.15
1628	99.32	.23
1629	99.66	.34
1630	99.77	.11
1631	99.85	.08
1632	99.92	.08
1634	99.96	.04
1635	100	.04

Subbasin # 3

Statistics: All elevations reported in meters

Min. Elevation: 1574
 Max. Elevation: 1663
 Mean. Elevation: 1615.55184534271
 Std. Deviation: 20.2867187995625

Elevation	% Area Below Elevation	% Area Subbasin
1574	.26	.26
1575	.79	.53
1576	1.05	.26
1577	1.85	.79
1578	2.9	1.05
1579	4.22	1.32
1580	5.98	1.76
1581	6.5	.53
1582	6.94	.44
1583	7.64	.7
1584	8.61	.97
1585	9.49	.88
1586	10.11	.62
1587	11.07	.97

1588	11.16	.09
1589	12.13	.97
1590	12.74	.62
1591	13.44	.7
1592	14.15	.7
1593	14.5	.35
1594	16.17	1.67
1595	17.75	1.58
1596	18.8	1.05
1597	19.51	.7
1598	20.65	1.14
1599	22.76	2.11
1600	25.4	2.64
1601	26.36	.97
1602	27.59	1.23
1603	28.65	1.05
1604	30.76	2.11
1605	33.39	2.64
1606	34.89	1.49
1607	36.2	1.32
1608	36.82	.62
1609	39.63	2.81
1610	42.09	2.46
1611	43.32	1.23
1612	44.46	1.14
1613	45.52	1.05
1614	48.68	3.16
1615	50.35	1.67
1616	51.67	1.32
1617	52.55	.88
1618	54.04	1.49
1619	56.15	2.11
1620	58.08	1.93
1621	59.23	1.14
1622	60.19	.97
1623	61.86	1.67
1624	64.24	2.37
1625	66.7	2.46
1626	68.28	1.58
1627	69.07	.79
1628	71.09	2.02
1629	73.11	2.02
1630	75.22	2.11
1631	76.63	1.41
1632	78.47	1.85
1633	79.53	1.05
1634	81.28	1.76
1635	82.43	1.14
1636	83.66	1.23
1637	84.27	.62
1638	85.24	.97
1639	86.03	.79
1640	87.52	1.49
1641	88.66	1.14
1642	89.19	.53

1643	89.89	.7
1644	91.21	1.32
1645	92.62	1.41
1646	93.76	1.14
1647	94.29	.53
1648	94.99	.7
1649	95.61	.62
1650	96.31	.7
1651	97.19	.88
1652	97.45	.26
1653	97.63	.18
1654	98.24	.62
1655	98.86	.62
1656	99.12	.26
1657	99.3	.18
1658	99.38	.09
1659	99.65	.26
1660	99.82	.18
1661	99.91	.09
1663	100	.09

Subbasin # 4

Statistics: All elevations reported in meters

Min. Elevation: 1526
 Max. Elevation: 1669
 Mean. Elevation: 1583.54308187344
 Std. Deviation: 30.0423405233007

Elevation	% Area Below Elevation	% Area Subbasin
1526	.04	.04
1527	.11	.07
1528	.21	.11
1529	.68	.46
1530	1.18	.5
1531	1.64	.46
1532	1.89	.25
1533	2.29	.39
1534	3.18	.89
1535	4.04	.86
1536	4.76	.72
1537	5.86	1.11
1538	6.79	.93
1539	7.65	.86
1540	8.4	.75
1541	8.97	.57
1542	9.8	.82
1543	10.65	.86
1544	11.76	1.11
1545	12.94	1.18
1546	13.41	.46

1547	14.09	.68
1548	14.66	.57
1549	16.16	1.5
1550	17.16	1
1551	17.7	.54
1552	18.41	.72
1553	19.38	.97
1554	20.2	.82
1555	21.42	1.22
1556	22.1	.68
1557	22.74	.64
1558	23.6	.86
1559	24.56	.97
1560	25.85	1.29
1561	26.71	.86
1562	27.35	.64
1563	28.28	.93
1564	29.14	.86
1565	30.07	.93
1566	31.46	1.39
1567	32.21	.75
1568	33.04	.82
1569	34.32	1.29
1570	35.72	1.39
1571	36.61	.89
1572	37.65	1.04
1573	38.47	.82
1574	39.72	1.25
1575	41.12	1.39
1576	42.26	1.14
1577	43.01	.75
1578	43.87	.86
1579	45.01	1.14
1580	46.19	1.18
1581	47.3	1.11
1582	48.7	1.39
1583	49.73	1.04
1584	50.91	1.18
1585	52.41	1.5
1586	53.49	1.07
1587	54.34	.86
1588	55.49	1.14
1589	56.67	1.18
1590	58.53	1.86
1591	59.78	1.25
1592	60.42	.64
1593	61.64	1.22
1594	63.35	1.72
1595	64.64	1.29
1596	65.89	1.25
1597	66.75	.86
1598	67.86	1.11
1599	69.57	1.72
1600	71.51	1.93
1601	72.33	.82

1602	73.26	.93
1603	73.83	.57
1604	74.97	1.14
1605	76.4	1.43
1606	77.33	.93
1607	78.08	.75
1608	78.83	.75
1609	79.98	1.14
1610	80.77	.79
1611	81.8	1.04
1612	82.16	.36
1613	82.84	.68
1614	83.73	.89
1615	84.59	.86
1616	85.31	.72
1617	85.98	.68
1618	86.66	.68
1619	87.67	1
1620	88.45	.79
1621	88.99	.54
1622	89.38	.39
1623	90.03	.64
1624	90.78	.75
1625	91.53	.75
1626	91.92	.39
1627	92.38	.46
1628	92.81	.43
1629	93.67	.86
1630	94.24	.57
1631	94.35	.11
1632	94.64	.29
1633	94.89	.25
1634	95.32	.43
1635	95.46	.14
1636	95.6	.14
1637	95.85	.25
1638	96.14	.29
1639	96.32	.18
1640	96.64	.32
1641	96.78	.14
1642	96.96	.18
1643	97.07	.11
1644	97.25	.18
1645	97.43	.18
1646	97.57	.14
1647	97.68	.11
1648	97.89	.21
1649	98.11	.21
1650	98.36	.25
1651	98.53	.18
1653	98.75	.21
1654	99	.25
1655	99.11	.11
1656	99.21	.11
1657	99.28	.07

1658	99.36	.07
1659	99.5	.14
1660	99.57	.07
1662	99.61	.04
1663	99.75	.14
1664	99.79	.04
1665	99.89	.11
1666	99.93	.04
1669	100	.07

Subbasin # 5

Statistics: All elevations reported in meters

Min. Elevation: 1537
 Max. Elevation: 1650
 Mean. Elevation: 1593.59594985535
 Std. Deviation: 24.2513324672649

Elevation	% Area Below Elevation	% Area Subbasin
1537	.1	.1
1538	.19	.1
1539	.39	.19
1540	.68	.29
1542	.77	.1
1543	1.06	.29
1544	1.83	.77
1545	2.31	.48
1546	2.7	.39
1547	2.99	.29
1548	3.38	.39
1549	3.47	.1
1550	3.66	.19
1551	3.86	.19
1552	4.15	.29
1553	4.44	.29
1554	5.21	.77
1555	5.69	.48
1556	6.56	.87
1557	6.75	.19
1558	7.04	.29
1559	8.29	1.25
1560	9.35	1.06
1561	9.93	.58
1562	10.99	1.06
1563	11.67	.68
1564	12.92	1.25
1565	14.37	1.45
1566	15.33	.96
1567	16.3	.96
1568	16.97	.68
1569	18.42	1.45

1570	20.25	1.83
1571	20.83	.58
1572	22.08	1.25
1573	23.14	1.06
1574	24.98	1.83
1575	27.19	2.22
1576	28.06	.87
1577	28.83	.77
1578	29.99	1.16
1579	31.63	1.64
1580	32.69	1.06
1581	33.94	1.25
1582	35.2	1.25
1583	36.26	1.06
1584	37.99	1.74
1585	39.34	1.35
1586	40.31	.96
1587	41.08	.77
1588	42.33	1.25
1589	43.88	1.54
1590	45.23	1.35
1591	46	.77
1592	47.06	1.06
1593	48.12	1.06
1594	49.95	1.83
1595	51.3	1.35
1596	52.36	1.06
1597	53.23	.87
1598	54.1	.87
1599	55.54	1.45
1600	57.86	2.31
1601	59.02	1.16
1602	59.98	.96
1603	61.04	1.06
1604	62.87	1.83
1605	65	2.12
1606	65.77	.77
1607	66.54	.77
1608	68.66	2.12
1609	70.97	2.31
1610	73.19	2.22
1611	74.35	1.16
1612	75.7	1.35
1613	77.05	1.35
1614	79.46	2.41
1615	81.29	1.83
1616	81.97	.68
1617	82.74	.77
1618	84.28	1.54
1619	85.82	1.54
1620	86.69	.87
1621	87.27	.58
1622	87.95	.68
1623	89.01	1.06
1624	90.07	1.06

1625	90.36	.29
1626	91.13	.77
1627	91.42	.29
1628	92.38	.96
1629	92.86	.48
1630	93.92	1.06
1631	94.12	.19
1632	94.79	.68
1633	95.27	.48
1634	95.66	.39
1635	96.62	.96
1636	97.01	.39
1637	97.97	.96
1638	98.07	.1
1641	98.26	.19
1642	98.55	.29
1643	98.84	.29
1644	99.13	.29
1645	99.32	.19
1646	99.42	.1
1647	99.61	.19
1648	99.71	.1
1649	99.9	.19
1650	100	.1

Subbasin # 6

Statistics: All elevations reported in meters

Min. Elevation: 1574
 Max. Elevation: 1684
 Mean. Elevation: 1617.87386256668
 Std. Deviation: 21.1531148155676

Elevation	% Area Below Elevation	% Area Subbasin
1574	.13	.13
1575	.44	.31
1576	.69	.25
1577	.97	.28
1578	1.19	.22
1579	1.63	.44
1580	2.54	.91
1581	3.42	.88
1582	4.3	.88
1583	5.05	.75
1584	6.34	1.29
1585	8.19	1.85
1586	9.26	1.07
1587	10.1	.85
1588	10.95	.85
1589	11.7	.75
1590	12.74	1.04

1591	13.3	.56
1592	13.99	.69
1593	14.68	.69
1594	16	1.32
1595	17.04	1.04
1596	17.95	.91
1597	19.05	1.1
1598	19.89	.85
1599	21.31	1.41
1600	23.22	1.91
1601	24.04	.82
1602	24.82	.78
1603	25.64	.82
1604	27.77	2.13
1605	29.59	1.82
1606	30.81	1.22
1607	31.88	1.07
1608	33.07	1.19
1609	34.89	1.82
1610	36.65	1.76
1611	38.12	1.47
1612	39.66	1.54
1613	40.92	1.26
1614	43.14	2.23
1615	45.31	2.17
1616	46.75	1.44
1617	47.82	1.07
1618	49.51	1.69
1619	51.87	2.35
1620	54.5	2.64
1621	56.13	1.63
1622	57.51	1.38
1623	58.8	1.29
1624	61.28	2.48
1625	63.79	2.51
1626	65.2	1.41
1627	66.8	1.6
1628	68.34	1.54
1629	70.51	2.17
1630	73.14	2.64
1631	74.14	1
1632	75.65	1.51
1633	76.66	1
1634	78.6	1.95
1635	80.01	1.41
1636	81.05	1.04
1637	82.08	1.04
1638	82.93	.85
1639	84.06	1.13
1640	85.35	1.29
1641	86.51	1.16
1642	87.61	1.1
1643	88.17	.56
1644	89.05	.88
1645	90.02	.97

1646	90.81	.78
1647	91.31	.5
1648	91.84	.53
1649	92.63	.78
1650	93.25	.63
1651	93.79	.53
1652	94.16	.38
1653	94.82	.66
1654	95.61	.78
1655	95.98	.38
1656	96.23	.25
1657	96.55	.31
1658	96.96	.41
1659	97.65	.69
1660	97.96	.31
1661	98.18	.22
1662	98.37	.19
1663	98.59	.22
1664	98.84	.25
1665	99	.16
1666	99.12	.13
1667	99.18	.06
1668	99.31	.13
1669	99.4	.09
1670	99.53	.13
1671	99.59	.06
1672	99.62	.03
1673	99.69	.06
1675	99.72	.03
1676	99.75	.03
1677	99.84	.09
1679	99.87	.03
1682	99.97	.09
1684	100	.03

Subbasin # 7

Statistics: All elevations reported in meters

Min. Elevation: 1536
 Max. Elevation: 1597
 Mean. Elevation: 1553.390625
 Std. Deviation: 19.6069449855572

Elevation	% Area Below Elevation	% Area Subbasin
1536	3.13	3.13
1537	9.38	6.25
1538	18.75	9.38
1539	29.69	10.94
1540	45.31	15.63
1541	48.44	3.13
1542	50	1.56

1543	53.13	3.13
1545	59.38	6.25
1548	60.94	1.56
1552	64.06	3.13
1554	68.75	4.69
1558	70.31	1.56
1560	71.88	1.56
1562	75	3.13
1567	76.56	1.56
1574	79.69	3.13
1575	82.81	3.13
1580	84.38	1.56
1582	85.94	1.56
1583	87.5	1.56
1587	89.06	1.56
1589	90.63	1.56
1590	92.19	1.56
1593	93.75	1.56
1594	96.88	3.13
1596	98.44	1.56
1597	100	1.56

Subbasin # 8

Statistics: All elevations reported in meters

Min. Elevation: 1539
 Max. Elevation: 1630
 Mean. Elevation: 1574.53731343284
 Std. Deviation: 21.1168918126433

Elevation	% Area Below Elevation	% Area Subbasin
1539	.6	.6
1540	1.34	.75
1541	2.09	.75
1542	2.39	.3
1543	3.28	.9
1544	4.63	1.34
1545	5.82	1.19
1546	7.31	1.49
1547	8.36	1.04
1548	10.9	2.54
1549	13.13	2.24
1550	14.93	1.79
1551	17.16	2.24
1552	18.51	1.34
1553	19.85	1.34
1554	22.84	2.99
1555	25.22	2.39
1556	26.72	1.49
1557	28.21	1.49
1558	29.1	.9

1559	31.19	2.09
1560	33.28	2.09
1561	34.63	1.34
1562	36.12	1.49
1563	36.87	.75
1564	38.21	1.34
1565	39.85	1.64
1566	41.04	1.19
1567	43.13	2.09
1568	44.48	1.34
1569	46.12	1.64
1570	47.31	1.19
1571	48.51	1.19
1572	50	1.49
1573	51.04	1.04
1574	51.49	.45
1575	52.84	1.34
1576	54.18	1.34
1577	55.52	1.34
1578	56.57	1.04
1579	57.91	1.34
1580	59.25	1.34
1581	60.3	1.04
1582	62.39	2.09
1583	63.43	1.04
1584	65.07	1.64
1585	66.57	1.49
1586	67.91	1.34
1587	68.96	1.04
1588	70.3	1.34
1589	72.24	1.94
1590	74.03	1.79
1591	75.52	1.49
1592	76.27	.75
1593	76.87	.6
1594	78.81	1.94
1595	80	1.19
1596	81.49	1.49
1597	82.24	.75
1598	84.33	2.09
1599	85.07	.75
1600	86.57	1.49
1601	87.91	1.34
1602	88.06	.15
1603	89.25	1.19
1604	90.45	1.19
1605	91.94	1.49
1606	92.84	.9
1607	93.58	.75
1608	94.18	.6
1609	96.27	2.09
1610	96.72	.45
1611	96.87	.15
1612	97.16	.3
1613	97.76	.6

1614	97.91	.15
1616	98.06	.15
1617	98.21	.15
1618	98.36	.15
1620	98.81	.45
1621	99.1	.3
1622	99.25	.15
1624	99.55	.3
1628	99.7	.15
1629	99.85	.15
1630	100	.15

Subbasin # 9

Statistics: All elevations reported in meters

Min. Elevation: 1539
 Max. Elevation: 1634
 Mean. Elevation: 1568.99322493225
 Std. Deviation: 20.8927923833794

Elevation	% Area Below Elevation	% Area Subbasin
1539	.95	.95
1540	3.52	2.57
1541	5.15	1.63
1542	6.5	1.36
1543	7.72	1.22
1544	10.16	2.44
1545	13.55	3.39
1546	14.23	.68
1547	15.72	1.49
1548	17.62	1.9
1549	19.11	1.49
1550	20.87	1.76
1551	23.17	2.3
1552	24.66	1.49
1553	26.29	1.63
1554	29.95	3.66
1555	32.66	2.71
1556	35.09	2.44
1557	37.8	2.71
1558	39.57	1.76
1559	42.01	2.44
1560	43.9	1.9
1561	44.72	.81
1562	46.34	1.63
1563	47.7	1.36
1564	49.46	1.76
1565	52.03	2.57
1566	52.71	.68
1567	53.79	1.08
1568	54.88	1.08

1569	57.72	2.85
1570	58.94	1.22
1571	60.43	1.49
1572	62.06	1.63
1573	63.14	1.08
1574	65.04	1.9
1575	66.67	1.63
1576	67.62	.95
1577	68.29	.68
1578	69.24	.95
1579	70.19	.95
1580	71.95	1.76
1581	73.04	1.08
1582	73.58	.54
1583	74.25	.68
1584	74.8	.54
1585	76.69	1.9
1586	77.24	.54
1587	78.32	1.08
1588	79	.68
1589	80.22	1.22
1590	81.57	1.36
1591	82.38	.81
1592	82.66	.27
1593	83.74	1.08
1594	85.09	1.36
1595	86.18	1.08
1596	87.13	.95
1597	87.8	.68
1598	88.75	.95
1599	89.57	.81
1600	90.24	.68
1601	90.79	.54
1602	91.06	.27
1603	91.6	.54
1604	92.55	.95
1605	94.17	1.63
1606	94.44	.27
1607	94.72	.27
1608	95.12	.41
1609	97.02	1.9
1611	97.15	.14
1612	97.29	.14
1613	97.7	.41
1614	97.97	.27
1615	98.1	.14
1617	98.24	.14
1618	98.37	.14
1619	98.64	.27
1620	98.78	.14
1621	99.19	.41
1622	99.32	.14
1623	99.59	.27
1624	99.73	.14
1626	99.86	.14

1634 100 .14

Subbasin # 10

Statistics: All elevations reported in meters

Min. Elevation: 1554
Max. Elevation: 1698
Mean. Elevation: 1624.44232922732
Std. Deviation: 30.0412265885751

Elevation	% Area Below Elevation	% Area Subbasin
1554	.15	.15
1555	.3	.15
1556	.37	.07
1557	.49	.11
1558	.6	.11
1559	.93	.34
1560	1.19	.26
1561	1.53	.34
1562	1.64	.11
1563	1.87	.22
1564	2.16	.3
1565	2.39	.22
1566	2.8	.41
1567	3.02	.22
1568	3.32	.3
1569	3.66	.34
1570	4.11	.45
1571	4.52	.41
1572	4.74	.22
1573	5.26	.52
1574	5.67	.41
1575	6.12	.45
1576	6.61	.49
1577	6.98	.37
1578	7.24	.26
1579	7.84	.6
1580	8.47	.63
1581	9.15	.67
1582	9.59	.45
1583	10.04	.45
1584	10.71	.67
1585	11.46	.75
1586	12.09	.63
1587	12.77	.67
1588	13.36	.6
1589	14.07	.71
1590	14.93	.86
1591	15.49	.56
1592	16.39	.9
1593	16.98	.6

1594	17.54	.56
1595	18.48	.93
1596	19.3	.82
1597	20.23	.93
1598	21.31	1.08
1599	22.02	.71
1600	23.07	1.05
1601	23.67	.6
1602	24.52	.86
1603	25.31	.78
1604	26.61	1.31
1605	27.96	1.34
1606	28.97	1.01
1607	29.56	.6
1608	30.72	1.16
1609	31.43	.71
1610	32.7	1.27
1611	33.82	1.12
1612	34.94	1.12
1613	36.02	1.08
1614	37.22	1.19
1615	38.6	1.38
1616	39.49	.9
1617	40.69	1.19
1618	41.77	1.08
1619	43.15	1.38
1620	44.27	1.12
1621	45.84	1.57
1622	46.66	.82
1623	47.93	1.27
1624	48.9	.97
1625	50.47	1.57
1626	51.33	.86
1627	52.48	1.16
1628	53.79	1.31
1629	55.13	1.34
1630	56.44	1.31
1631	57.89	1.46
1632	58.6	.71
1633	59.84	1.23
1634	61.18	1.34
1635	62.19	1.01
1636	63.12	.93
1637	64.28	1.16
1638	64.95	.67
1639	66.63	1.68
1640	68.16	1.53
1641	69.06	.9
1642	69.91	.86
1643	71.07	1.16
1644	71.89	.82
1645	73.35	1.46
1646	74.69	1.34
1647	75.59	.9
1648	76.86	1.27

1649	77.9	1.05
1650	79.13	1.23
1651	80.14	1.01
1652	81.04	.9
1653	81.6	.56
1654	82.9	1.31
1655	84.06	1.16
1656	84.99	.93
1657	85.55	.56
1658	86.11	.56
1659	87.23	1.12
1660	87.87	.63
1661	88.35	.49
1662	88.99	.63
1663	89.62	.63
1664	90.33	.71
1665	91.27	.93
1666	92.05	.78
1667	92.57	.52
1668	93.17	.6
1669	93.77	.6
1670	94.33	.56
1671	94.74	.41
1672	95.11	.37
1673	95.6	.49
1674	96.23	.63
1675	96.53	.3
1676	96.75	.22
1677	96.94	.19
1678	97.31	.37
1679	97.5	.19
1680	97.95	.45
1681	98.21	.26
1682	98.32	.11
1683	98.47	.15
1684	98.77	.3
1685	98.81	.04
1686	98.99	.19
1687	99.07	.07
1689	99.1	.04
1690	99.29	.19
1691	99.4	.11
1693	99.51	.11
1694	99.59	.07
1695	99.7	.11
1696	99.85	.15
1697	99.96	.11
1698	100	.04

Subbasin # 11

Statistics: All elevations reported in meters

Min. Elevation: 1552
 Max. Elevation: 1677
 Mean. Elevation: 1611.42953929539
 Std. Deviation: 25.8109367157051

Elevation	% Area Below Elevation	% Area Subbasin
1552	.03	.03
1553	.07	.03
1554	.17	.1
1555	.61	.44
1556	1.02	.41
1557	1.46	.44
1558	1.63	.17
1559	2.03	.41
1560	2.3	.27
1561	2.74	.44
1562	2.95	.2
1563	3.25	.3
1564	3.62	.37
1565	4.07	.44
1566	4.44	.37
1567	4.71	.27
1568	4.95	.24
1569	5.52	.58
1570	6.23	.71
1571	6.61	.37
1572	6.94	.34
1573	7.45	.51
1574	8.16	.71
1575	9.04	.88
1576	9.89	.85
1577	10.33	.44
1578	10.84	.51
1579	11.92	1.08
1580	12.91	.98
1581	13.79	.88
1582	14.53	.75
1583	15.62	1.08
1584	16.73	1.12
1585	17.89	1.15
1586	18.46	.58
1587	19.28	.81
1588	20.12	.85
1589	21.34	1.22
1590	22.53	1.19
1591	23.1	.58
1592	24.59	1.49
1593	25.34	.75
1594	27.13	1.8
1595	29	1.86
1596	30.08	1.08
1597	30.93	.85
1598	32.45	1.52
1599	33.71	1.25

1600	35.23	1.52
1601	36.45	1.22
1602	37.5	1.05
1603	38.99	1.49
1604	40.75	1.76
1605	42.07	1.32
1606	43.36	1.29
1607	44.68	1.32
1608	46.17	1.49
1609	47.32	1.15
1610	49.22	1.9
1611	50.64	1.42
1612	51.83	1.19
1613	52.91	1.08
1614	54.1	1.19
1615	56.1	2
1616	57.62	1.52
1617	58.23	.61
1618	59.38	1.15
1619	60.43	1.05
1620	62.2	1.76
1621	63.52	1.32
1622	64.94	1.42
1623	65.79	.85
1624	66.97	1.19
1625	68.33	1.36
1626	69.55	1.22
1627	70.39	.85
1628	71.48	1.08
1629	73.04	1.56
1630	74.39	1.36
1631	75.85	1.46
1632	76.73	.88
1633	77.78	1.05
1634	79.3	1.52
1635	80.49	1.19
1636	81.57	1.08
1637	82.59	1.02
1638	83.43	.85
1639	84.32	.88
1640	85.5	1.19
1641	86.38	.88
1642	87.23	.85
1643	88.18	.95
1644	89.33	1.15
1645	90.31	.98
1646	91.09	.78
1647	91.67	.58
1648	92.24	.58
1649	92.78	.54
1650	93.36	.58
1651	94.04	.68
1652	94.55	.51
1653	95.12	.58
1654	95.6	.47

1655	96.1	.51
1656	96.44	.34
1657	96.71	.27
1658	97.26	.54
1659	97.56	.3
1660	97.9	.34
1661	98.2	.3
1662	98.27	.07
1663	98.51	.24
1664	98.95	.44
1665	99.09	.14
1666	99.19	.1
1667	99.25	.07
1668	99.46	.2
1669	99.63	.17
1670	99.66	.03
1671	99.8	.14
1672	99.83	.03
1673	99.9	.07
1675	99.93	.03
1676	99.97	.03
1677	100	.03

Subbasin # 12

Statistics: All elevations reported in meters

Min. Elevation: 1549
 Max. Elevation: 1649
 Mean. Elevation: 1583.17213114754
 Std. Deviation: 23.5752456509091

Elevation	% Area Below Elevation	% Area Subbasin
1549	.27	.27
1550	2.46	2.19
1551	3.55	1.09
1552	6.01	2.46
1553	8.74	2.73
1554	12.02	3.28
1555	14.75	2.73
1556	15.3	.55
1557	16.67	1.37
1558	17.49	.82
1559	20.22	2.73
1560	22.68	2.46
1561	24.86	2.19
1562	25.14	.27
1563	25.96	.82
1564	26.78	.82
1565	28.42	1.64
1566	29.23	.82
1567	30.6	1.37

1568	32.51	1.91
1569	33.61	1.09
1570	36.07	2.46
1571	37.16	1.09
1572	38.52	1.37
1573	40.16	1.64
1574	41.53	1.37
1575	42.9	1.37
1576	44.26	1.37
1577	45.63	1.37
1578	46.99	1.37
1579	48.91	1.91
1580	50	1.09
1581	50.82	.82
1582	52.73	1.91
1583	54.37	1.64
1584	55.46	1.09
1585	56.83	1.37
1586	58.2	1.37
1587	59.84	1.64
1588	61.75	1.91
1589	62.3	.55
1590	63.39	1.09
1591	65.03	1.64
1592	67.21	2.19
1593	68.31	1.09
1594	69.67	1.37
1595	70.77	1.09
1596	71.58	.82
1597	72.95	1.37
1598	74.04	1.09
1599	76.23	2.19
1600	77.6	1.37
1602	78.42	.82
1603	79.23	.82
1604	80.87	1.64
1605	81.97	1.09
1606	82.24	.27
1607	82.79	.55
1608	83.61	.82
1609	84.15	.55
1610	85.52	1.37
1611	85.79	.27
1612	86.61	.82
1613	86.89	.27
1614	87.16	.27
1615	87.43	.27
1616	87.98	.55
1617	88.8	.82
1618	90.16	1.37
1619	90.71	.55
1621	91.53	.82
1622	92.08	.55
1623	92.35	.27
1624	93.17	.82

1626	94.54	1.37
1627	95.36	.82
1628	95.63	.27
1629	96.17	.55
1630	96.72	.55
1631	97.27	.55
1632	97.81	.55
1633	98.09	.27
1634	98.63	.55
1635	98.91	.27
1636	99.18	.27
1638	99.45	.27
1642	99.73	.27
1649	100	.27

Subbasin # 13

Statistics: All elevations reported in meters

Min. Elevation: 1556
Max. Elevation: 1684
Mean. Elevation: 1614.80952380952
Std. Deviation: 28.2731027905411

Elevation	% Area Below Elevation	% Area Subbasin
1556	.21	.21
1557	.63	.42
1558	.85	.21
1559	1.59	.74
1561	1.8	.21
1562	2.33	.53
1563	2.75	.42
1564	3.07	.32
1565	3.6	.53
1566	4.13	.53
1567	4.44	.32
1568	4.76	.32
1569	5.4	.63
1570	6.14	.74
1571	6.77	.63
1572	7.2	.42
1573	7.83	.63
1574	7.94	.11
1575	8.78	.85
1576	9.74	.95
1577	10.69	.95
1578	11.11	.42
1579	12.28	1.16
1580	12.59	.32
1581	13.33	.74
1582	14.6	1.27
1583	15.03	.42

1584	16.19	1.16
1585	17.25	1.06
1586	18.84	1.59
1587	19.79	.95
1588	21.27	1.48
1589	21.8	.53
1590	22.43	.63
1591	23.39	.95
1592	24.44	1.06
1593	25.19	.74
1594	26.56	1.38
1595	27.51	.95
1596	28.47	.95
1597	29.63	1.16
1598	31.11	1.48
1599	32.38	1.27
1600	33.02	.63
1601	34.71	1.69
1602	35.45	.74
1603	36.61	1.16
1604	37.88	1.27
1605	38.94	1.06
1606	39.47	.53
1607	40.63	1.16
1608	41.8	1.16
1609	43.07	1.27
1610	44.23	1.16
1611	45.08	.85
1612	46.98	1.9
1613	48.47	1.48
1614	49.42	.95
1615	50.9	1.48
1616	52.7	1.8
1617	53.76	1.06
1618	54.5	.74
1619	55.45	.95
1620	57.35	1.9
1621	58.41	1.06
1622	59.89	1.48
1623	61.16	1.27
1624	62.22	1.06
1625	63.17	.95
1626	64.23	1.06
1627	65.29	1.06
1628	66.67	1.38
1629	67.72	1.06
1630	68.78	1.06
1631	70.48	1.69
1632	71.22	.74
1633	71.85	.63
1634	72.8	.95
1635	73.86	1.06
1636	75.34	1.48
1637	76.72	1.38
1638	77.57	.85

1639	78.41	.85
1640	79.58	1.16
1641	80.42	.85
1642	81.38	.95
1643	82.65	1.27
1644	83.39	.74
1645	84.55	1.16
1646	85.08	.53
1647	86.14	1.06
1648	86.56	.42
1649	87.3	.74
1650	88.25	.95
1651	88.78	.53
1652	89.31	.53
1653	89.95	.63
1654	90.69	.74
1655	91.75	1.06
1656	92.38	.63
1657	93.02	.63
1658	93.44	.42
1659	94.39	.95
1660	95.13	.74
1661	95.45	.32
1662	95.98	.53
1663	96.19	.21
1664	96.93	.74
1665	97.46	.53
1666	97.67	.21
1667	97.99	.32
1668	98.1	.11
1671	98.2	.11
1672	98.31	.11
1673	98.62	.32
1674	98.94	.32
1675	99.15	.21
1676	99.26	.11
1679	99.37	.11
1680	99.47	.11
1681	99.68	.21
1682	99.89	.21
1684	100	.11

Subbasin # 14

Statistics: All elevations reported in meters

Min. Elevation: 1556
 Max. Elevation: 1685
 Mean. Elevation: 1624.37278106509
 Std. Deviation: 26.9354427255476

Elevation	% Area Below Elevation	% Area Subbasin
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1556	.05	.05
1557	.23	.18
1558	.5	.27
1559	1	.5
1560	1.09	.09
1561	1.32	.23
1562	1.5	.18
1563	1.59	.09
1564	1.73	.14
1565	1.96	.23
1566	2.41	.46
1567	2.73	.32
1568	2.87	.14
1569	3.14	.27
1570	3.46	.32
1571	3.73	.27
1572	3.91	.18
1573	4.42	.5
1574	4.82	.41
1575	5.19	.36
1576	5.51	.32
1577	5.92	.41
1578	6.24	.32
1579	6.6	.36
1580	7.01	.41
1581	7.24	.23
1582	7.69	.46
1583	8.28	.59
1584	9.15	.86
1585	9.65	.5
1586	10.42	.77
1587	10.88	.46
1588	11.33	.46
1589	11.97	.64
1590	12.84	.86
1591	13.34	.5
1592	14.34	1
1593	14.93	.59
1594	15.79	.86
1595	16.89	1.09
1596	18.02	1.14
1597	18.66	.64
1598	19.39	.73
1599	20.3	.91
1600	21.03	.73
1601	21.39	.36
1602	22.26	.86
1603	23.53	1.27
1604	24.53	1
1605	25.44	.91
1606	26.72	1.27
1607	27.77	1.05
1608	28.63	.86
1609	29.63	1
1610	30.77	1.14

1611	31.77	1
1612	32.64	.86
1613	33.45	.82
1614	34.5	1.05
1615	35.64	1.14
1616	36.37	.73
1617	37.6	1.23
1618	38.78	1.18
1619	39.96	1.18
1620	40.56	.59
1621	41.78	1.23
1622	42.88	1.09
1623	43.97	1.09
1624	45.24	1.27
1625	46.79	1.55
1626	47.75	.96
1627	48.79	1.05
1628	49.98	1.18
1629	51.43	1.46
1630	53.21	1.78
1631	54.53	1.32
1632	55.71	1.18
1633	56.94	1.23
1634	58.53	1.59
1635	59.81	1.27
1636	61.22	1.41
1637	62.81	1.59
1638	64.54	1.73
1639	66	1.46
1640	67.41	1.41
1641	68.78	1.37
1642	70	1.23
1643	71.64	1.64
1644	73.65	2
1645	75.74	2.09
1646	77.2	1.46
1647	78.29	1.09
1648	79.65	1.37
1649	81.38	1.73
1650	82.89	1.5
1651	84.34	1.46
1652	85.34	1
1653	86.75	1.41
1654	88.44	1.68
1655	89.62	1.18
1656	90.94	1.32
1657	91.44	.5
1658	92.17	.73
1659	93.31	1.14
1660	94.13	.82
1661	94.45	.32
1662	94.9	.46
1663	95.58	.68
1664	96.13	.55
1665	96.54	.41

1666	96.86	.32
1667	97.22	.36
1668	97.41	.18
1669	97.68	.27
1670	98.09	.41
1671	98.41	.32
1672	98.45	.05
1673	98.63	.18
1674	99	.36
1675	99.09	.09
1676	99.27	.18
1677	99.36	.09
1678	99.41	.05
1679	99.5	.09
1680	99.59	.09
1682	99.73	.14
1683	99.82	.09
1684	99.95	.14
1685	100	.05

Subbasin # 15

Statistics: All elevations reported in meters

Min. Elevation: 1553
 Max. Elevation: 1684
 Mean. Elevation: 1612.71183717193
 Std. Deviation: 27.4498760619955

Elevation	% Area Below Elevation	% Area Subbasin
1553	.11	.11
1554	.32	.21
1555	.8	.48
1556	1.02	.21
1557	1.18	.16
1558	1.61	.43
1559	1.93	.32
1560	2.46	.54
1561	2.79	.32
1562	3.48	.7
1563	3.96	.48
1564	4.39	.43
1565	5.03	.64
1566	5.62	.59
1567	6.21	.59
1568	6.91	.7
1569	7.5	.59
1570	8.03	.54
1571	8.41	.37
1572	8.89	.48
1573	9.59	.7
1574	10.28	.7

1575	11.09	.8
1576	12	.91
1577	12.43	.43
1578	13.02	.59
1579	13.87	.86
1580	15	1.12
1581	15.8	.8
1582	16.55	.75
1583	17.14	.59
1584	17.89	.75
1585	18.85	.96
1586	19.93	1.07
1587	20.57	.64
1588	21.26	.7
1589	22.44	1.18
1590	23.25	.8
1591	24.1	.86
1592	24.96	.86
1593	25.6	.64
1594	27.05	1.45
1595	28.55	1.5
1596	29.3	.75
1597	30.21	.91
1598	30.96	.75
1599	32.35	1.39
1600	33.37	1.02
1601	34.55	1.18
1602	35.73	1.18
1603	36.74	1.02
1604	37.92	1.18
1605	39.37	1.45
1606	40.22	.86
1607	41.24	1.02
1608	42.37	1.12
1609	43.81	1.45
1610	45.31	1.5
1611	46.22	.91
1612	47.78	1.55
1613	49.06	1.29
1614	50.35	1.29
1615	51.04	.7
1616	52.06	1.02
1617	53.78	1.71
1618	55.12	1.34
1619	56.51	1.39
1620	57.95	1.45
1621	59.29	1.34
1622	60.69	1.39
1623	62.08	1.39
1624	63.79	1.71
1625	65.67	1.87
1626	66.63	.96
1627	67.49	.86
1628	68.61	1.12
1629	69.79	1.18

1630	70.97	1.18
1631	72.84	1.87
1632	74.13	1.29
1633	75.31	1.18
1634	76.54	1.23
1635	77.99	1.45
1636	79.22	1.23
1637	80.13	.91
1638	81.57	1.45
1639	82.7	1.12
1640	83.66	.96
1641	84.9	1.23
1642	86.07	1.18
1643	86.98	.91
1644	88.22	1.23
1645	89.13	.91
1646	89.93	.8
1647	90.63	.7
1648	91.11	.48
1649	91.97	.86
1650	92.45	.48
1651	92.72	.27
1652	93.2	.48
1653	93.73	.54
1654	94.22	.48
1655	94.7	.48
1656	95.18	.48
1657	95.5	.32
1658	95.77	.27
1659	96.14	.37
1660	96.63	.48
1661	96.95	.32
1662	97.32	.37
1663	97.59	.27
1664	97.91	.32
1665	98.07	.16
1666	98.39	.32
1667	98.5	.11
1668	98.55	.05
1669	98.88	.32
1670	99.04	.16
1671	99.14	.11
1673	99.2	.05
1674	99.36	.16
1675	99.46	.11
1676	99.63	.16
1677	99.68	.05
1680	99.79	.11
1683	99.84	.05
1684	100	.16

APPENDIX C

HYDROLOGICAL RESPONSE UNITS DISTRIBUTION REPORT

SWAT model simulation Date: 1/7/2024 12:00:00 AM Time: 00:00:00
MULTIPLE HRUs LandUse/Soil/Slope OPTION THRESHOLDS : 30 / 10 / 10 [%]
Number of HRUs: 72
Number of Subbasins: 15

	Area [ha]	Area[acres]	
Watershed	133034.1043	328733.9234	

LANDUSE:	Area [ha]	Area[acres]	%Wat.Area
Pasture --> PAST	53096.1224	131203.1732	39.91
Agricultural Land-Row Crops --> AGRR	79727.6929	197011.1155	59.93
Wetlands-Mixed --> WETL	210.2890	519.6347	0.16

SOILS:	Area [ha]	Area[acres]	%Wat.Area
Lc64-2b-722	10369.1663	25622.7284	7.79
Vc1-3a-954	122664.9380	303111.1950	92.21

SLOPE:	Area [ha]	Area[acres]	%Wat.Area
3.35-9999	20388.3466	50380.6238	15.33
1.07-3.35	98141.3547	242512.1945	73.77
0-1.07	14504.4030	35841.1050	10.90

		Area [ha]	Area[acres]	%Wat.Area		%Sub.Area	
SUBBASIN #		1	1785.5793	4412.2556		1.34	
LANDUSE:							
	Pasture --> PAST	783.5995	1936.3136	0.59		43.88	
	Agricultural Land-Row Crops --> AGRR	1001.9797	2475.9420	0.75		56.12	
SOILS:							
	Lc64-2b-722	1785.5793	4412.2556	1.34		100.00	
SLOPE:							
	3.35-9999	443.1833	1095.1282	0.33		24.82	
	1.07-3.35	1104.7469	2729.8848	0.83		61.87	
	0-1.07	237.6490	587.2427	0.18		13.31	
HRUs							
1	Pasture --> PAST/Lc64-2b-722/3.35-9999		276.1867	682.4712	0.21	15.47	1
2	Pasture --> PAST/Lc64-2b-722/1.07-3.35		423.9145	1047.5139	0.32	23.74	2
3	Pasture --> PAST/Lc64-2b-722/0-1.07		83.4983	206.3285	0.06	4.68	3
4	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/0-1.07		154.1507	380.9142	0.12	8.63	4
5	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/3.35-9999		166.9966	412.6570	0.13	9.35	5
6	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/1.07-3.35		680.8324	1682.3709	0.51	38.13	6
		Area [ha]	Area[acres]	%Wat.Area		%Sub.Area	
SUBBASIN #		2	15005.6251	37079.6499		11.28	
LANDUSE:							
	Pasture --> PAST	6984.1522	17258.1893	5.25		46.54	
	Agricultural Land-Row Crops --> AGRR	8021.4729	19821.4606	6.03		53.46	
SOILS:							
	Lc64-2b-722	4689.2578	11587.3906	3.52		31.25	

Vc1-3a-954		10316.3673	25492.2593	7.75	68.75	
SLOPE:						
1.07-3.35		9797.5052	24210.1253	7.36	65.29	
0-1.07		4149.4844	10253.5834	3.12	27.65	
3.35-9999		1058.6355	2615.9412	0.80	7.05	
HRUs						
7	Pasture --> PAST/Lc64-2b-722/1.07-3.35	1357.0428	3353.3206	1.02	9.04	1
8	Pasture --> PAST/Lc64-2b-722/0-1.07	490.2406	1211.4090	0.37	3.27	2
9	Pasture --> PAST/Lc64-2b-722/3.35-9999	568.3949	1404.5322	0.43	3.79	3
10	Pasture --> PAST/Vc1-3a-954/0-1.07	1692.8488	4183.1139	1.27	11.28	4
11	Pasture --> PAST/Vc1-3a-954/1.07-3.35	2875.6252	7105.8136	2.16	19.16	5
12	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/0-1.07	525.7653	1299.1923	0.40	3.50	6
13	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/1.07-3.35	1257.5737	3107.5275	0.95	8.38	7
14	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/3.35-9999	490.2406	1211.4090	0.37	3.27	8
15	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	4307.2636	10643.4637	3.24	28.70	9
16	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07	1440.6298	3559.8682	1.08	9.60	10

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #		3	6410.0606	15839.5801	4.82
LANDUSE:					
Pasture --> PAST		2641.2689	6526.7075	1.99	41.21
Agricultural Land-Row Crops --> AGRR		3768.7917	9312.8727	2.83	58.79
SOILS:					
Vc1-3a-954		6410.0606	15839.5802	4.82	100.00
SLOPE:					
0-1.07		1367.5442	3379.2700	1.03	21.33
1.07-3.35		5042.5164	12460.3102	3.79	78.67
HRUs					
17	Pasture --> PAST/Vc1-3a-954/0-1.07	675.9645	1670.3422	0.51	10.55

18	Pasture --> PAST/Vc1-3a-954/1.07-3.35	1965.3043	4856.3653	1.48	30.66	2
19	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07	691.5796	1708.9278	0.52	10.79	3
20	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	3077.2121	7603.9449	2.31	48.01	4
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #		4	15754.7798	38930.8487	11.84	
LANDUSE:						
	Agricultural Land-Row Crops --> AGRR	15754.7798	38930.8487	11.84	100.00	
SOILS:						
	Lc64-2b-722	3894.3292	9623.0821	2.93	24.72	
	Vc1-3a-954	11860.4506	29307.7665	8.92	75.28	
SLOPE:						
	1.07-3.35	12287.3615	30362.6846	9.24	77.99	
	3.35-9999	1998.4182	4938.1913	1.50	12.68	
	0-1.07	1469.0001	3629.9727	1.10	9.32	
HRUs						
21	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/1.07-3.35	3414.2064	8436.6747	2.57	21.67	1
22	Agricultural Land-Row Crops --> AGRR/Lc64-2b-722/3.35-9999	480.1228	1186.4074	0.36	3.05	2
23	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999	1518.2954	3751.7839	1.14	9.64	3
24	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07	1469.0001	3629.9727	1.10	9.32	4
25	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	8873.1551	21926.0099	6.67	56.32	5

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #		5	5841.1536	14433.7827	4.39	
LANDUSE:						
	Pasture --> PAST	2740.4687	6771.8351	2.06	46.92	
	Agricultural Land-Row Crops --> AGRR	3100.6849	7661.9475	2.33	53.08	
SOILS:						
	Vc1-3a-954	5841.1536	14433.7826	4.39	100.00	
SLOPE:						
	3.35-9999	798.1262	1972.2097	0.60	13.66	
	1.07-3.35	3962.3787	9791.2359	2.98	67.84	
	0-1.07	1080.6487	2670.3371	0.81	18.50	
HRUs						
26	Pasture --> PAST/Vc1-3a-954/3.35-9999		416.7208	1029.7378	0.31	7.13
27	Pasture --> PAST/Vc1-3a-954/1.07-3.35		1808.1443	4468.0149	1.36	30.96
28	Pasture --> PAST/Vc1-3a-954/0-1.07		515.6036	1274.0824	0.39	8.83
29	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999		381.4054	942.4719	0.29	6.53
30	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07		565.0451	1396.2547	0.42	9.67
31	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35		2154.2344	5323.2209	1.62	36.88
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #		6	17951.5492	44359.1757	13.49	
LANDUSE:						
	Pasture --> PAST	6532.4219	16141.9410	4.91	36.39	
	Agricultural Land-Row Crops --> AGRR	11419.1274	28217.2348	8.58	63.61	
SOILS:						
	Vc1-3a-954	17951.5493	44359.1758	13.49	100.00	

SLOPE:

1.07-3.35	13272.3835	32796.7233	9.98	73.93
0-1.07	4679.1657	11562.4525	3.52	26.07

HRUs

32	Pasture --> PAST/Vc1-3a-954/1.07-3.35	4398.7162	10869.4477	3.31	24.50	1
33	Pasture --> PAST/Vc1-3a-954/0-1.07	2133.7056	5272.4933	1.60	11.89	2
34	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	8873.6673	21927.2755	6.67	49.43	3
35	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07	2545.4601	6289.9592	1.91	14.18	4

	Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	7	360.4955	890.8024	0.27

LANDUSE:

Wetlands-Mixed --> WETL	210.2890	519.6347	0.16	58.33
Agricultural Land-Row Crops --> AGRR	150.2065	371.1677	0.11	41.67

SOILS:

Vc1-3a-954	360.4955	890.8024	0.27	100.00
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SLOPE:

0-1.07	158.9026	392.6563	0.12	44.08
1.07-3.35	201.5929	498.1461	0.15	55.92

HRUs

36	Wetlands-Mixed --> WETL/Vc1-3a-954/0-1.07	135.1858	334.0509	0.10	37.50	1
37	Wetlands-Mixed --> WETL/Vc1-3a-954/1.07-3.35	75.1032	185.5838	0.06	20.83	2
38	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	126.4896	312.5622	0.10	35.09	3
39	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07	23.7168	58.6054	0.02	6.58	4

	Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	8	3773.9372	9325.5876	2.84

LANDUSE:						
	Pasture --> PAST	1549.4359	3828.7336	1.16	41.06	
	Agricultural Land-Row Crops --> AGRR	2224.5013	5496.8540	1.67	58.94	
SOILS:						
	Vc1-3a-954	3773.9372	9325.5876	2.84	100.00	
SLOPE:						
	3.35-9999	752.2158	1858.7628	0.57	19.93	
	0-1.07	630.0611	1556.9124	0.47	16.70	
	1.07-3.35	2391.6604	5909.9124	1.80	63.37	
HRUs						
40	Pasture --> PAST/Vc1-3a-954/3.35-9999	507.9064	1255.0620	0.38	13.46	1
41	Pasture --> PAST/Vc1-3a-954/0-1.07	186.4466	460.7190	0.14	4.94	2
42	Pasture --> PAST/Vc1-3a-954/1.07-3.35	855.0829	2112.9526	0.64	22.66	3
43	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	1536.5775	3796.9599	1.16	40.72	4
44	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07	443.6144	1096.1934	0.33	11.75	5
45	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999	244.3094	603.7007	0.18	6.47	6
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #		9	4156.9637	10272.0652	3.12	
LANDUSE:						
	Pasture --> PAST	2334.5508	5768.7918	1.75	56.16	
	Agricultural Land-Row Crops --> AGRR	1822.4129	4503.2734	1.37	43.84	
SOILS:						
	Vc1-3a-954	4156.9637	10272.0652	3.12	100.00	
SLOPE:						
	1.07-3.35	3225.4823	7970.3281	2.42	77.59	
	0-1.07	731.9471	1808.6779	0.55	17.61	

3.35-9999		199.5343	493.0591	0.15	4.80		
HRUs							
46	Pasture --> PAST/Vc1-3a-954/1.07-3.35		1861.9982	4601.0907	1.40	44.79	1
47	Pasture --> PAST/Vc1-3a-954/0-1.07		472.5526	1167.7011	0.36	11.37	2
48	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999		199.5343	493.0591	0.15	4.80	3
49	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35		1363.4841	3369.2374	1.02	32.80	4
50	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/0-1.07		259.3945	640.9769	0.19	6.24	5
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area		
SUBBASIN #		10	15090.1163	37288.4318	11.34		
LANDUSE:							
Pasture --> PAST		6422.5236	15870.3769	4.83	42.56		
Agricultural Land-Row Crops --> AGRR		8667.5927	21418.0549	6.52	57.44		
SOILS:							
Vc1-3a-954		15090.1162	37288.4317	11.34	100.00		
SLOPE:							
1.07-3.35		11063.0346	27337.3118	8.32	73.31		
3.35-9999		4027.0816	9951.1200	3.03	26.69		
HRUs							
51	Pasture --> PAST/Vc1-3a-954/1.07-3.35		4360.7288	10775.5790	3.28	28.90	1
52	Pasture --> PAST/Vc1-3a-954/3.35-9999		2061.7947	5094.7979	1.55	13.66	2
53	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999		1965.2868	4856.3221	1.48	13.02	3
54	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35		6702.3058	16561.7328	5.04	44.42	4
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area		
SUBBASIN #		11	16627.8548	41088.2606	12.50		

LANDUSE:						
	Pasture --> PAST	7441.7494	18388.9348	5.59	44.75	
	Agricultural Land-Row Crops --> AGRR	9186.1055	22699.3259	6.91	55.25	
SOILS:						
	Vc1-3a-954	16627.8548	41088.2607	12.50	100.00	
SLOPE:						
	3.35-9999	3623.5114	8953.8777	2.72	21.79	
	1.07-3.35	13004.3435	32134.3830	9.78	78.21	
HRUs						
55	Pasture --> PAST/Vc1-3a-954/3.35-9999		1923.1487	4752.1966	1.45	11.57
56	Pasture --> PAST/Vc1-3a-954/1.07-3.35		5518.6007	13636.7382	4.15	33.19
57	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35		7485.7428	18497.6448	5.63	45.02
58	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999		1700.3626	4201.6811	1.28	10.23
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #		12	2061.5836	5094.2762	1.55	
LANDUSE:						
	Agricultural Land-Row Crops --> AGRR	2061.5836	5094.2762	1.55	100.00	
SOILS:						
	Vc1-3a-954	2061.5836	5094.2762	1.55	100.00	
SLOPE:						
	3.35-9999	490.8532	1212.9229	0.37	23.81	
	1.07-3.35	1570.7304	3881.3533	1.18	76.19	
HRUs						
59	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999		490.8532	1212.9229	0.37	23.81
60	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35		1570.7304	3881.3533	1.18	76.19

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #		13	5322.9414	13153.2543	4.00	
LANDUSE:						
	Pasture --> PAST	3201.2973	7910.5656	2.41	60.14	
	Agricultural Land-Row Crops --> AGRR	2121.6441	5242.6886	1.59	39.86	
SOILS:						
	Vc1-3a-954	5322.9413	13153.2542	4.00	100.00	
SLOPE:						
	1.07-3.35	4016.3055	9924.4916	3.02	75.45	
	3.35-9999	1306.6359	3228.7625	0.98	24.55	
HRUs						
61	Pasture --> PAST/Vc1-3a-954/1.07-3.35		2265.4342	5598.0011	1.70	42.56
62	Pasture --> PAST/Vc1-3a-954/3.35-9999		935.8631	2312.5645	0.70	17.58
63	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999		370.7728	916.1980	0.28	6.97
64	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35		1750.8713	4326.4906	1.32	32.89
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #		14	12375.1345	30579.5761	9.30	
LANDUSE:						
	Pasture --> PAST	6320.7998	15619.0124	4.75	51.08	
	Agricultural Land-Row Crops --> AGRR	6054.3347	14960.5638	4.55	48.92	
SOILS:						
	Vc1-3a-954	12375.1345	30579.5762	9.30	100.00	
SLOPE:						
	3.35-9999	3736.2788	9232.5316	2.81	30.19	
	1.07-3.35	8638.8558	21347.0445	6.49	69.81	
HRUs						

65	Pasture --> PAST/Vc1-3a-954/3.35-9999	1898.2381	4690.6412	1.43	15.34	1
66	Pasture --> PAST/Vc1-3a-954/1.07-3.35	4422.5617	10928.3711	3.32	35.74	2
67	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999	1838.0407	4541.8904	1.38	14.85	3
68	Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	4216.2940	10418.6734	3.17	34.07	4

	Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	15	10516.3296	25986.3763	7.90	
LANDUSE:					
Pasture --> PAST	6143.8544	15181.7715	4.62	58.42	
Agricultural Land-Row Crops --> AGRR	4372.4752	10804.6048	3.29	41.58	
SOILS:					
Vc1-3a-954	10516.3296	25986.3763	7.90	100.00	
SLOPE:					
1.07-3.35	8562.4571	21158.2596	6.44	81.42	
3.35-9999	1953.8725	4828.1167	1.47	18.58	
HRUs					
69 Pasture --> PAST/Vc1-3a-954/1.07-3.35	4720.6221	11664.8932	3.55	44.89	1
70 Pasture --> PAST/Vc1-3a-954/3.35-9999	1423.2323	3516.8783	1.07	13.53	2
71 Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/1.07-3.35	3841.8350	9493.3663	2.89	36.53	3
72 Agricultural Land-Row Crops --> AGRR/Vc1-3a-954/3.35-9999	530.6402	1311.2384	0.40	5.05	4

APPENDIX D

VOLUME OF WATER USE (m³/m) WITHIN QUATERNARY CATCHMENT B11C–B11D

REGISTERED VOLUME BILLING PERIOD January 2004 - December 2004																					
Office ID	Office Name	WMA ID	WMA Name	Source ID	Source Name	Sector ID	Sector Name	Drainage ID	Drainage Code	Jan-04	Feb-04	Mar-04	Apr-04	May-04	Jun-04	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	902	AGRICULTURE: IRRIGATION	1291	B11C	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	910	INDUSTRY (URBAN)	1291	B11C	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1291	B11C	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1292	B11D	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1293	B11E	99450.08	99450.08	99450.08	99450.08	99450.08	99450.08	99450.08	99450.08	99450.08	99450.08	99450.08	99450.08
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	920	WATER SUPPLY SERVICE	1293	B11E	106682.17	106682.17	106682.17	106682.17	106682.17	106682.17	106682.17	106682.17	106682.17	106682.17	106682.17	106682.17
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1291	B11C	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1292	B11D	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1293	B11E	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	904	COMMERCIAL	1292	B11D	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33

5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	904	COMMERCIAL	1293	B11E	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92
5	MPUMALANGA OFFICE	3539	OLIFANTS	899	SPRING/EYE	902	AGRICULTURE: IRRIGATION	1291	B11C	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33

REGISTERED VOLUME BILLING PERIOD January 2005 - December 2005																					
Office ID	Office Name	WMA ID	WMA Name	Source ID	Source Name	Sector ID	Sector Name	Drainage ID	Drainage Code	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	902	AGRICULTURE: IRRIGATION	1291	B11C	41.66667	41.66667	41.66667	41.66667	41.66667	41.66667	41.66667	41.66667	41.66667	41.66667	41.66667	41.66667
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	1257.5	1257.5	1257.5	1257.5	1257.5	1257.5	1257.5	1257.5	1257.5	1257.5	1257.5	1257.5
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	291.66667	291.66667	291.66667	291.66667	291.66667	291.66667	291.66667	291.66667	291.66667	291.66667	291.66667	291.66667
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	304.16667	304.16667	304.16667	304.16667	304.16667	304.16667	304.16667	304.16667	304.16667	304.16667	304.16667	304.16667
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	910	INDUSTRY (URBAN)	1291	B11C	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333	2372.58333
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1291	B11C	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1292	B11D	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333	77310.8333
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1293	B11E	99450.0833	99450.0833	106103.417	106103.417	106103.417	106103.417	106103.417	106103.417	106103.417	106103.417	106103.417	106103.417
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	250	250	250	250	250	250	250	250	250	250	250	250
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	612.5	612.5	612.5	612.5	612.5	612.5	612.5	612.5	612.5	612.5	612.5	612.5
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	920	WATER SUPPLY SERVICE	1293	B11E	106682.167											
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1291	B11C	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333	23333.3333
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1292	B11D	30927	30927	30927	30927	30927	30927	30927	30927	30927	30927	30927	30927
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1293	B11E	60000	60000	60000	60000	60000	60000	60000	60000	60000	60000	60000	60000
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	101.66667	101.66667	101.66667	101.66667	101.66667	101.66667	101.66667	101.66667	101.66667	101.66667	101.66667	101.66667
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	727.91667	727.91667	727.91667	727.91667	727.91667	727.91667	727.91667	727.91667	727.91667	727.91667	727.91667	727.91667
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	904	COMMERCIAL	1292	B11D	60.33333	60.33333	60.33333	60.33333	60.33333	60.33333	60.33333	60.33333	60.33333	60.33333	60.33333	60.33333
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	904	COMMERCIAL	1293	B11E	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667	1242.91667
5	MPUMALANGA OFFICE	3539	OLIFANTS	899	SPRING/EYE	902	AGRICULTURE: IRRIGATION	1291	B11C	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333	4783.33333

REGISTERED VOLUME BILLING PERIOD January 2006 - December 2006																					
Office ID	Office Name	WMA ID	WMA Name	Source ID	Source Name	Sector ID	Sector Name	Drainage ID	Drainage Code	Jan-06	Feb-06	Mar-06	Apr-06	May-06	Jun-06	Jul-06	Aug-06	Sep-06	Oct-06	Nov-06	Dec-06
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	902	AGRICULTURE: IRRIGATION	1291	B11C	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67

5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	910	INDUSTRY (URBAN)	1291	B11C	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1291	B11C	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1292	B11D	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1293	B11E	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	920	WATER SUPPLY SERVICE	1293	B11E												
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STR EAM	902	AGRICULTURE: IRRIGATION	1291	B11C	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STR EAM	902	AGRICULTURE: IRRIGATION	1292	B11D	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STR EAM	902	AGRICULTURE: IRRIGATION	1293	B11E	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STR EAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STR EAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STR EAM	904	COMMERCIAL	1292	B11D	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STR EAM	904	COMMERCIAL	1293	B11E	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92
5	MPUMALANGA OFFICE	3539	OLIFANTS	899	SPRING/EYE	902	AGRICULTURE: IRRIGATION	1291	B11C	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33

REGISTERED VOLUME BILLING PERIOD January 2007 - December 2007																					
Office ID	Office Name	WMA ID	WMA Name	Source ID	Source Name	Sector ID	Sector Name	Drainage ID	Drainage Code	Jan-07	Feb-07	Mar-07	Apr-07	May-07	Jun-07	Jul-07	Aug-07	Sep-07	Oct-07	Nov-07	Dec-07
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	902	AGRICULTURE: IRRIGATION	1291	B11C	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	910	INDUSTRY (URBAN)	1291	B11C	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58

5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1291	B11C	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1292	B11D	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1293	B11E	106103.42	106103.42	106103.42	106103.42	106103.42	106103.42	123203.42	106103.42	92651.83	92651.83	92651.83	92651.83
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	920	WATER SUPPLY SERVICE	1293	B11E												
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1291	B11C	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33	23333.33
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1292	B11D	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00	30927.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	902	AGRICULTURE: IRRIGATION	1293	B11E	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00	60000.00
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	904	COMMERCIAL	1292	B11D	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33
5	MPUMALANGA OFFICE	3539	OLIFANTS	897	RIVER/STREAM	904	COMMERCIAL	1293	B11E	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92
5	MPUMALANGA OFFICE	3539	OLIFANTS	899	SPRING/EYE	902	AGRICULTURE: IRRIGATION	1291	B11C	4783.33	4783.33	4783.33	4783.33	4783.33	4783.33						

REGISTERED VOLUME BILLING PERIOD January 2008 - December 2008

Office ID	Office Name	WMA ID	WMA Name	Source ID	Source Name	Sector ID	Sector Name	Drainage ID	Drainage Code	Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08	Aug-08	Sep-08	Oct-08	Nov-08	Dec-08
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	902	AGRICULTURE: IRRIGATION	1291	B11C	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67	41.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50	1257.50
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67	291.67
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17	304.17
5	MPUMALANGA OFFICE	3539	OLIFANTS	891	BOREHOLE	910	INDUSTRY (URBAN)	1291	B11C	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58	2372.58
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1291	B11C	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25	104737.25
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1292	B11D	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83	77310.83
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	902	AGRICULTURE: IRRIGATION	1293	B11E	92651.83	92651.83	92651.83	92651.83	92651.83	92651.83	92651.83	92651.83	92651.83	92651.83	92651.83	92651.83
5	MPUMALANGA OFFICE	3539	OLIFANTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00

5	MPUMALANGA OFFICE	3539	OLIFA NTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75	861.75
5	MPUMALANGA OFFICE	3539	OLIFA NTS	893	DAM	903	AGRICULTURE: WATERING LIVESTOCK	1293	B11E	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50	612.50
5	MPUMALANGA OFFICE	3539	OLIFA NTS	893	DAM	920	WATER SUPPLY SERVICE	1293	B11E												
5	MPUMALANGA OFFICE	3539	OLIFA NTS	897	RIVER/STR EAM	902	AGRICULTURE: IRRIGATION	1291	B11C	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3	23333.3 3
5	MPUMALANGA OFFICE	3539	OLIFA NTS	897	RIVER/STR EAM	902	AGRICULTURE: IRRIGATION	1292	B11D	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0	30927.0 0
5	MPUMALANGA OFFICE	3539	OLIFA NTS	897	RIVER/STR EAM	902	AGRICULTURE: IRRIGATION	1293	B11E	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0	60000.0 0
5	MPUMALANGA OFFICE	3539	OLIFA NTS	897	RIVER/STR EAM	903	AGRICULTURE: WATERING LIVESTOCK	1291	B11C	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67	101.67
5	MPUMALANGA OFFICE	3539	OLIFA NTS	897	RIVER/STR EAM	903	AGRICULTURE: WATERING LIVESTOCK	1292	B11D	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92	727.92
5	MPUMALANGA OFFICE	3539	OLIFA NTS	897	RIVER/STR EAM	904	COMMERCIAL	1292	B11D	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33	60.33
5	MPUMALANGA OFFICE	3539	OLIFA NTS	897	RIVER/STR EAM	904	COMMERCIAL	1293	B11E	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92	1242.92
5	MPUMALANGA OFFICE	3539	OLIFA NTS	899	SPRING/EY E	902	AGRICULTURE: IRRIGATION	1291	B11C												