

**Evaluation of the impact of land use/land cover changes on water
balance in the C81F quaternary catchment of the Eastern Free
State, South Africa**

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ABSTRACT

South Africa is amongst the countries grappling with water scarcity issues. This means the assessment of this resource and its management is very important. Water balance components need to be assessed in a catchment and this can be done by understanding catchment-level hydrologic processes requiring hydrological models. This study aims to evaluate the impact of land use/land cover (LULC) changes on the water balance in the study area, namely the C81F quaternary catchment of the Eastern Free State, South Africa, under the Thabo Mofutsanyane District Municipality. A SWAT model was used for the simulation of streamflow. The model inputs were digital elevation model (DEM), LULC maps for 1990 and 2018, and soil maps and slope data created using the ArcGIS spatial analysis tool. A warm-up period of three years was used. The analysed LULC changes in 1990 showed that the least dominant classes were water and barren land, the most dominant was pasture and urban, followed by mixed forest which accounted for 71.44%, 16.73%, and 5.50% of the total area, respectively. However, the analysed LULC changes for 2018 showed the most dominant to be pasture, followed by urban, and generic agricultural land, comprising 65.08%, 18.82%, and 7.96%, respectively. Generic agricultural land, urban and pasture are the major LULC classes that impacted the water balance components. SWAT-CUP was used for calibration and validation, and a program called Sequential Uncertainty Fitting Version 2 (SUFI2) was chosen as one of the stochastic calibration programs in SWAT-CUP. The calibration flow data from 1993 to 2007 was used and the validation flow data was from 2008 to 2018. The effectiveness of the SWAT model was assessed using two widely used modelling evaluation techniques, namely quantitative statistics and graphical techniques. The model's effectiveness was assessed using Nash-Sutcliffe criteria (NSE), Coefficient of Determination (R^2), and percentage of bias (PBIAS). Calibration resulted in R^2 and PBIAS and NSE being 0.79, 0.72, and -3.6, respectively, and these results were deemed very good. Validation results for the same parameters were also found to be good at 0.72, 0.69, and 10, respectively. The model performance for calibration was very good and good at the validation stage, according to monthly ratings of model performance. The decrease of evapotranspiration by 0.7 mm was steady and may be linked to the increase in generic agricultural land. More results showed a decrease in percolation and lateral flow of 0.13 mm and 3.39 mm, respectively. Furthermore, surface runoff increased by

4.24 mm, and the adjusted SWAT parameters reflect and quantify the increased built-up area's effects, which increased surface runoff and decreased percolation in the basin. The increase in stream flow is related to an increase in urban areas, and it is recommended that more studies should be done on this catchment to assess the potential impacts of climate change on groundwater and water balance.

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ABBREVIATIONS

95PPU	Ninety-Five Percent Predictive Uncertainties
ACRU	Agricultural Catchments Research Unit
ARC	Agricultural Research Council
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
ArcSWAT	ArcGIS Graphical user Interface for SWAT
AWC	Available Water Capacity
BARR	Barren
CCLM	COSMO Climate Limited area Model
CN	Daily Curve Number
CO ₂	Carbon Dioxide
DEM	Digital Elevation Model
DWS	Department of Water and Sanitation
ET	Evapotranspiration
FAO-UNESCO	Food and Agriculture Organization - The United Nations Educational, Scientific and Cultural Organization
FRST	Mixed forest
AGRL	Generic Agricultural Land
GIS	Geographic Information Systems
GLUE	Generalised Likelihood Uncertainty Estima
GSFLOW	Groundwater and Surface-water FLOW model
HBV	Hydrologiska Byrans Vattenavdelning model
HRU	Hydrological Response Unit
LULC	Land Use Land Cover
m	Meters
MAP	Mean Annual Precipitation
MCMC	Markov Chain Monte Carlo
mm	Millimetres
NASA	US National Aeronautics and Space Administration
NSE	Nash Sutcliffe Efficiency

ParaSol	Parameter Solution
PAST	Pasture
PET	Potential Evapotranspiration
PRMS	Precipitation Runoff Modelling System
r	Pearson's Correlation Coefficient
R ²	Coefficient of Determination
RΔ	Rate of change
SA	South Africa
SANLC	South African National Land Cover
SAWS	South African Weather Services
SCS-CN	Soil Conservation Service - curve number
SRTM	Shuttle Radar Topography Mission
SUF2	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment
SWAT-CUP	SWAT Model Calibration and Uncertainty Procedures
URBN	Urban
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VSR	Variable Storage Routing
WATR	Water
WETL	Wetlands
WGEN	Weather Generator Module
WGS	World Geodetic System
WRSM	Water Resources Simulation Model

CHAPTER 1: BACKGROUND OF THE STUDY

4.2 Introduction

It is widely reported that water is a scarce resource in South Africa and the country is classified to be water-stressed due to low rainfall (Welderufael et al., 2013). In addition, Rand Water (2021) reported that the reason why South Africa is classified to be a water-stressed country is because it receives an annual rainfall of 492 millimeter (mm) despite evapotranspiration exceeding 2000 mm per year. As Rand Water (2021) further posits, South Africa has a scarcity of freshwater resulting from decreasing water quality that results from perpetual pollution activities and the devastation of river catchments (Mocwagae, 2020). Notably, the main drivers of decreasing water quality are urbanisation, deforestation, damming of rivers, and destruction of wetlands (Rand Water, 2021; Muyambo et al., 2023).

In light of the above, it is important to acknowledge that the destruction of river catchments has impacted land use which changed throughout the years and water as a resource has been impacted by these changes in a complex way (Prins et al., 2022). For example, afforestation normally changes the water cycle through increased transpiration, increased interception, and decreased soil moisture, which affects the moderate catchment water balance negatively (Welderufael et al., 2013). According to Lin et al. (2007) and Albhaisi et al. (2013), the impact of land-use change in a catchment affects the water supply through the alteration of hydrological procedures such as runoff, baseflow, groundwater and infiltration. Altering land-use patterns within the catchment can also alter the natural hydrologic conditions of the catchment (Kabanda & Palamuleni, 2013).

It should be underscored that the hydrological impact on downstream catchment water availability is influenced by rainwater harvesting, which refers to the gathering of surface runoff on the upstream catchment for upstream water consumption (Welderufael et al., 2013; Botai et al., 2016). Based on this, the C81F quaternary catchment in the Eastern Free State is already facing a challenge of low rainfall and drought, resulting in water scarcity in the agricultural, municipal water supply, industrial and environmental sectors (Muyambo et al., 2023). A study conducted by Donnefeld et al. (2018) revealed that the Free State province experienced increased

water challenges. On that note, as the demand for water increases in the province, both quantity and quality are decreasing to critical levels.

It is also worth highlighting that the activities on the C81F quaternary catchment are mostly subsistence and commercial farming, which require more water for irrigation purposes (Gibson et al., 2018). Since the study area is mountainous, the upstream part receives more rain and the downstream receives less (Aleman et al., 2016). Despite this, the whole area needs water to sustain its various activities (Botai et al., 2016). However, prolonged drought results in reduced irrigation which impacts on the water (Mocwagae, 2020). This has consequently led to recurring drought episodes (Prins et al., 2022). As such, the current drought in the Free State province has had devastating effects on the agriculture dependants where the economy has been damaged beyond 50% in terms of employees and revenue losses (Gibson et al., 2018; Muyambo et al., 2023). On that note, more than 80% of businesses have lost more than 50% of their employees owing to the drought that is taking a toll on the province (Hlalele et al., 2015; Mocwagae, 2020).

In addition, dam levels in the province are not at the expected capacity and they normally fill to not more than 62.55%, which is lower than the average capacity of 73.33% (Donnefeld et al., 2018). Notably, the mentioned compounding factors are a cause for concern as the recurring drought episodes, decimated surface water sources and drying up of boreholes call for the urgent need for supplementary feeding mechanisms across the province (Gibson et al., 2018). In order to evaluate these adverse impacts of water availability, the Geographic Information System (GIS) and Remote Sensing techniques were used together with a Soil Water Assessment Tool (SWAT) hydrological model to estimate the impact of land use/land cover (LULC) changes on the catchment's water balance.

Furthermore, the SWAT model can simulate the impacts of land management/administration practices, land-use change, and rainfall-runoff processes with meticulous detail by dividing the catchment into sub-basins (Botai et al., 2016). Against this backdrop, a SWAT model was adopted to simulate the hydrology of the C81F quaternary catchment in the Thabo Mofutsanyane District Municipality in the Free State Province of South Africa.

1.2 Problem Statement

Despite the clear linkages on the nexus between LULC changes, water availability and quality in South Africa, there is a dearth of knowledge on how LULC is posing challenges to water resources and drought in quaternary catchments (Local Government Climate Change Support Program (LGCCSP), 2016; Mocwagae, 2020). The dearth of research in that landscape includes the catchments in the Thabo Mofutsanyane District Municipality of the Free State Province (Muyambo et al., 2023). As Prins et al. (2022) put across, the C81F quaternary catchment in the Thabo Mofutsanyane District has changed its LULC over the years and continues to change at a rapid rate, which calls for evaluation. In the same vein, the agricultural fields have been changing nearly every three years and much of the land is no longer forested, as it used to be (Mocwagae, 2020).

As the LGCCSP (2016) and Donnefeld et al. (2018) argue, the municipality is currently experiencing issues of water scarcity with low quality; this problem can be expected to worsen because of drought, reduced runoff, and increased evaporation which continues to be experienced by this region. Again, the C81F is plagued with low rainfall, drought, and low streamflow which are attributed to LULC changes (Donnefeld et al., 2018). In light of the preceding, this study evaluated the impact of LULC changes on the limited water resources that are affected in the catchment's water balance (Calzadilla et al., 2014; Nkhonjera, 2017). Despite facing water shortage conundrums in the past years, South Africa has struggled to devise equitable and rational mechanisms to manage the now-scarce resource (Donnefeld et al., 2018; Rand Water, 2021).

The impact of low rainfall in the Free State province has contributed to the low average dam levels. As articulated earlier, the dam levels in the province sit below the datum average of 62.55% and the dam capacity is at an average of 73.33%, which in turn has ripple effects on the agricultural area with an estimated 1,145,000 hectares that were planted in 2018/19 (Agri-SA, 2019; Mocwagae, 2020). Considering the preceding discussion, in response to the mentioned gap, this study intends to formulate mitigation strategies to be implemented for the limited water resources in the C81F quaternary catchment, among other sustainable measures.

1.3 Research question and sub-questions

Main research question:

- How does the impact of land use/land cover (LULC) changes affect the water balance in C81F quaternary catchment?

Sub-questions:

- What are the changes in LULC in the catchment for the period of 1990 to 2018?
- What are the impacts of LULC changes on the water balance for the period of 1990 to 2018?
- Which strategies can be implemented for the management of limited water resources in the C81F quaternary catchment?

1.4 Research Aim and Objectives

This study is aimed at evaluating the impacts of LULC changes on water balance in C81F quaternary catchment by applying the remotely sensed data such as satellite imagery, in conjunction with ArcGIS and the SWAT model. To achieve this aim of the study, three research objectives have been formulated, as follows:

- To determine LULC changes in the catchment for the period of 1990 to 2018;
- To analyse the impact of LULC changes on water balance for the period of 1990 to 2018, and
- To develop the mitigation strategies to be implemented for the limited water resources in the C81F quaternary catchment.

1.5 Scope of the study

The scope of the study is limited to the following:

- To evaluate the LULC changes on the water balance in C81F quaternary catchment of the Free State, South Africa.
- The methodology includes the use of ArcGIS, Remote sensing, and SWAT model on the catchment water balance evaluation.
- The period of study is restricted to the period of 1990 to 2018.

1.6 Importance of the study

This study has utmost importance as it intends to provide strategies to build resilient water infrastructure and nature-based solutions that address the conundrum of water shortages, water pollution and drought. In this view, the study will help formulate adaptation strategies that can enhance the management of limited water resources and provide data and knowledge to key stakeholders in the basin. Equally, the findings of this study will contribute to the literature on climate change and LUCL changes impact on water resource planning in South Africa. The findings of the study are also valuable to water resource management, and rural and urban planners. Similarly, hydrologists, land managers, and ecologists are also poised to benefit from this study as it will provide a baseline for understanding the consequences of LUCL on water resources.

1.7 Outline of Research

The thesis is categorised into five chapters and structured as follows:

- Chapter 1: This chapter outlines the background and introduction of the study, which includes the problem statement, research questions, aim and objectives, and overview of the research methodology adopted in the study. The chapter also captures the limitations as well as the value of the research.
- Chapter 2: This chapter presents the relevant available literature on this field of study. It will include an overview of land-use scenarios, Impacts of LULC changes on water balance, impacts of climate change on water resources, detection of a change in LULC using satellite data/imagery and hydrological modelling of previous studies analysed, considered, and used as guidelines.
- Chapter 3: This chapter presents an overview of the study area in terms of topography, drainage, and catchment area, LULC, soil and climate aspects.
- Chapter 4: This chapter emphasises the research methodology and the materials used. It discusses the LULC map, using remote sensing, ArcGIS, and the SWAT model.
- Chapter 5: This chapter focuses on the main results, their interpretation and discussion.

- Chapter 6: The final chapter consists of the main conclusion regarding the results obtained in the research and the recommendations emerging from this research.

1.8 Chapter Summary

This chapter succinctly provided the introduction and background of the study. Furthermore, it highlighted the research problem, the aim and objectives, the main research question, sub-questions, and assumptions. The main research question, which is: “*How does the impact of LULC changes affect the water balance in the C81F quaternary catchment?*”, will be answered by using remote sensing, GIS and the SWAT model. The chapter mainly articulated the gaps in studying water balances in South Africa’s catchments which prompted this study to evaluate the impacts of LULC changes on water balance in the C81F quaternary catchment by applying the remotely sensed data. The next chapter focuses on the literature that was reviewed in tandem with the objectives of the study.

CHAPTER 2: LITERATURE REVIEW

2.1 An overview of the land use scenarios

According to Paul and Rashid. (2017), land-use change is a process whereby anthropogenic factors (human activities) alter the natural landscape, meaning how the land has been utilised, which signals the use of land for socio-economic activities. From the viewpoint of Verburg et al. (2004), land cover is any physical and biological covering on the earth's surface, for instance, water, vegetation, soil, and artificial structures (Verburg et al., 2004). The rate at which land use is changing globally and locally is rapidly increasing and it is remarkable (Gibson et al., 2018). These changes are visible in natural vegetation, crops, forest plantations, water sources and natural vegetation (Yira et al., 2016). Notably, the changes can be ascribed to a range of variables, including rapid urbanisation, overgrazing, bush encroachment, soil erosion, and climate change (Gillson et al., 2012; Gibson et al., 2018).

In light of the above, it should be underscored that drivers of land use change have migrated from a simplistic representation to a more nuanced understanding that encompasses an interplay between different spatial and temporal scales (Lambin et al., 2003; Gabiri et al., 2020). In this view, Kutter et al. (1997) and Woyesa and Welderufael (2011) argue that land use depends on biophysical and socio-economic factors. On that note, biophysical factors such as climate, soil, topography, and vegetation mostly affect the runoff of a particular catchment (Aleman et al., 2016). These factors also include the socio-economic drivers that possibly affect land-use change, including population increase and its level of influence (Namugize et al., 2018). Prins et al. (2022) investigated the nexus between LULC and water quality in the uMgeni River catchment, in South Africa. The study found that the uMgeni Catchment's LULC has significantly changed since 1994 as a result of the expansion of urban areas, the destruction of natural vegetation, and the cultivation of new land.

According to Lambin et al. (2003), the effects of land-use change are adverse as they are closely linked to the continued decrease in food production, fibre production, and efficient use of resources in wealth and well-being. Similarly, the negative impact of land-use change is also observed through the structural and behavioural factors linked to the demands in technological capacity, and social relations affecting demand and capacity (Obahoundje et al., 2017). As Gyamfi et al. (2016) note, the

downstream land-use change has an off-side effect and upstream users might bring forth an important on-site effect on the catchment's water resources. Following this, the commercial afforestation in South Africa has also resulted in the reduction of estimated streamflow due to the region experiencing lower and more marginal rainfall (Gush et al., 2002; Gabiri et al., 2019).

LULC change is one of the major factors affecting the groundwater system through intense human activities including: industrialisation, mining, urbanisation, agriculture, which resulted in significant and clear changes in the landscape with impact on the water balance of surface and groundwater system (Albhaisi et al., 2013; Yira et al., 2016). Furthermore, the conversion of land use from grassland to afforestation is being driven by the demand for fibre and wood (Gibson et al., 2018). That being the case, efforts for ecosystem restoration which alters the earth's systems are disturbing water and nutrient use which is further aggravated by LULC and climate change (Donnefeld et al., 2018). Similarly, Ahirwal et al. (2021) contend that protecting our forests and addressing climate change threats requires a limitation in agricultural expansion on natural forests and abstracted lands.

An important factor that influences the generation of streamflow in a catchment is the land cover. The flow at the catchment outlet is altered by a change in land use or land cover to forecast how a change in land use will affect streamflow at the outlet (Saha et al., 2019). However Kumar et al. (2022) adds that climate change and LULC are two significant factors that have an impact on the dynamics of hydrology at the local, regional, and global levels, ultimately having an impact on people and the environment. Rapid socioeconomic development and population growth are the main forces behind LULC. Anand et al. (2018), did a study that finds out that changes in land use caused by logging, cropland loss, and urbanisation have increased mean annual stream flow and, as a result, decreased mean annual evapotranspiration for some sub-basins. These problems include population growth and the rising need for land for agriculture, habitation, and production to meet the needs of this expanding population. Therefore, it becomes crucial to assess whether ET is changing with changing land cover or is resilient in catchments with plantation crops that are also changing over time. Additionally, unlike natural systems, which allow results to be directly applied, the spatial-temporal dynamics of land cover change, climate change, human development, vegetation growth, and water cycling have not been

simultaneously assessed over agricultural and forest plantation landscapes (Chemura et al., 2020). Urbanisation-related construction has led to a significant amount of natural permeable areas being replaced by impermeable surface areas, which has reduced evapotranspiration (Liu et al., 2023).

2.2 Impacts of LULC changes on water balance

The socio-economic development drives (LULC) changes, which potentially have a large impact on water resources (Larbi et al., 2020). These adverse changes have a bearing on the partitioning of precipitation thereby impacting evaporation, evapotranspiration, interception and infiltration of surface and groundwater (Yira et al., 2016; Gyamfi et al., 2016). The quantity and quality of water resources would be impacted by land use change, such as urbanisation, when combined with climate (Awotwi et al., 2015; Tong et al., 2012). For instance, when an area is being converted into an urban setting, this urbanisation transition may be driven by an interplay of factors such as proximity to road networks, proximity to existing urban areas and similar topographic drivers such as flatter areas (Gibson et al., 2018).

There is an unquestionable connection between climate change, destabilised water balance, drought, and food security (Ahmed, 2020). Climate change is a reality, and its impacts include perpetual dry spells, and erratic rainfall patterns which in turn have a bearing on agricultural production (Bahta et al., 2016; Parsons et al., 2019). The devastating impacts of climate change are leading to the decimation of water sources which is affecting diverse socioeconomic activities in developing countries (Wei et al., 2011; Orimoloye et al., 2019; Anand et al., 2018). As Orimoloye et al. (2019) argue, more often, drought is firstly determined by the scarcity of water for agricultural and domestic use which then affects the provision of water to streams, rivers and dams, thus affecting water bodies, soil moisture, groundwater, ecosystems, wetlands and human action.

According to Saha et al. (2019), the rising temperatures and unpredictable rainfall patterns brought on by climate change and unpredictability are one of the elements affecting water balance and streamflow in LULC land-use change. According to Aliyari et al. (2021), successful water management for industrial, agricultural, and municipal usage throughout Africa and beyond depends on the evaluation of climate change implications on water flow patterns and groundwater availability. The impacts

of changes in LULC permeate into atmospheric components such as precipitation and temperature, according to Saddique et al. (2020). To that end, it alters a watershed's stream flow, base flow, and evapotranspiration water balance (Larbi et al., 2020).

Numerous studies have demonstrated that one of the primary drivers of changes in water balance is changes in LULC (Schilling et al., 2008; Chemura et al., 2020) brought on by an increase in anthropogenic activities (such as agriculture, urbanisation, and overgrazing) (Togbévi & Sintondji, 2021). Due to the complexity of hydrological processes and variations in land use in different regions, there hasn't been a strong correlation between different land use types and runoff generation mechanisms, and hydrologists and water resources managers continue to debate the potential effects of past and ongoing changes in land use (Anand et al., 2018). Liu, Rong and Wei. (2023) argues that even though all land use types combined to have an impact on the water balance, one land use type has the greatest impact on the elements of the water balance. According to Botai et al. (2016), the population growth dynamics are leading to the expansion of urban area, and the natural environment is not being spared in the process.

2.3 Impacts of climate change on water resources

Climate change variations are felt in every sector and section of society (Kusangaya et al., 2014). Whereas climate change issues are visible in sectors such as agriculture, energy, health, transport, food supply, the built environment and forest resources, water resources are heavily impacted (Leisner, 2020). In African countries, agriculture and water resources are the sectors that are reeling from climate change impacts (Kusanyaya et al., 2014). As such, climate change directly affects the spatial and temporal availability of resources and productivity in these sectors (Beyaitan Bantin et al., 2017). Furthermore, climate change is expected to change the patterns of precipitation and temperature and it may therefore affect water supply, the hydrological cycle, river discharge, and seasonal and local water availability (Huntington, 2006; Shrestha et al., 2016). Consequently, the climate change conundrum poses significant risks to agricultural production and water resources, which in turn has an impact on the health of the economy and

environmental systems, making it difficult to allocate and effectively manage water and land resources (Aghapour Sabbaghi et al., 2020).

According to Nkhonjera (2017), climate change accounts for changes in the hydrological cycle which is consequently leading to various risks, including water availability. Taking the issue of water resource planning and management seriously is therefore crucial (Fant et al., 2015; Brown & Wilby, 2012; Haasnoot & Middelkoop, 2012). The consequences of climate change on South Africa's water resource systems have been the subject of numerous research studies (Kusangaya et al., 2014; Fant et al., 2015; Nkhonjera, 2017; Mpandeli et al., 2017; Nyahunda & Tirivangasi, 2022). A study conducted by Poorsepahy-Samian et al. (2016), also unearthed that water supply is affected by climate change through hydrologic extremes which is, in turn, causing drought risks and flooding.

The increase in water demand is mainly associated with population growth and socioeconomic development and is leading to a decrease in water availability owing to climate and anthropogenic changes (Kusanyaya et al., 2014). This has brought about water allocation conundrums in most developing countries (Medellín-Azuara et al., 2010; Ojo et al., 2021; Adeagbo et al., 2021; Muyambo et al., 2023). Following this, in most developing countries, poor farmers are reeling from low production risks posed by climate change, though the challenges might be different across nations or regions (Ojo et al., 2021).

In most African countries, South Africa included, people largely depend on rain-fed agriculture and other natural resource-based strategies for livelihood. However, these sectors are vulnerable to erratic rainfall patterns and rising temperatures stemming from climate change and variability (Liyame et al., 2008; Call et al., 2019). As Nyahunda and Tirivangasi (2022) posit, South Africa is among the African countries that are susceptible to the slightest impacts of climate change and variability. As such, the rapid climate change has great bearings on water and soil resources supply, especially under arid and semi-arid conditions, as precipitation patterns are greatly affected together with carbon dioxide concentration and temperature rise (Huq & Ayers, 2007; Mpandeli et al., 2017).

Consequently, Mpandeli et al. (2017) further denote that the management of water resources is becoming a daunting task in the face of climate change. As such, climate

change exacerbated by human activities, threatens water supplies by altering the amount of precipitation that is partitioned into streamflow and evapotranspiration (Bouraoui et al., 1998; Menzel et al., 2007; Caldwell et al., 2016; Lu et al., 2019). It is noteworthy that the understanding of climate change and human activities is critical as such activities alter the streamflow from forested headwater catchments (Gabiri et al., 2020). Furthermore, the increased intensity of precipitation caused by climate change accelerates the rates of flood risks, decimation of surface runoff, and decreased rates of groundwater recharge (Trenberth, 2011; Lu et al., 2019).

According to Wang et al. (2012), and supported by Saddique et al. (2020), high temperature rises and soaring evapotranspiration owing to climate change are impeding the viability of irrigation services which is the major consumer of water under present circumstances. Notably, Mengistu et al. (2021) used the COSMO Climate Limited-area Model (CCLM), a Regional Climate Model (RCM), in conjunction with a hydrological SWAT model to examine the effects of climate change on water resources in the Upper Blue Nile (Abay) River Basin (Mengistu et al., 2021). According to the findings, evapotranspiration will rise to unheard-of levels by up to 27%, and surface runoff will likely rise by up to 14%. The study also found that the basin's overall water production has been declining at an unprecedented rate. Due to the consequences of such changes to the hydrologic balance on water management in the basin, which is now typical in most water catchments in Africa, (Gibson et al., 2018).

2.4 Detecting change in LULC using satellite data/imagery

Scholars such as Ozesmi and Bauer (2002) and Wasige et al. (2013) postulate that the knowledge of techniques used for detecting change of LULC on the earth's surface is very important. For any type of development or planning, such knowledge is essential to obtaining consistent and in-depth information on the research area (Majumder, 2010; Gong & Liu, 2013). Given this, remote sensing has been utilised to provide fine-grained information about land cover and its associated changes over vast and difficult-to-access territories for more than 40 years (Wasige et al., 2013). As Peter et al. (2018) mention, the usage of remote sensing is far better than field-based survey methods because it is not labour-intensive. As such, the biophysical surface attributes such as moisture surface, vegetation cover, heterogeneity and

superficial soil organic matter content can be observed on Earth by providing repetitive and spatial measurements using satellite sensors (Lambin et al., 2003).

Notably, the Geographic Information Systems (GIS) are used in adaptable situations to gather, extract, and manipulate data, and also to display spatial information which is usable in decision-making (Bouraoui et al., 1998). From the argument advanced by Albhaisi et al. (2013), the integration of remote sensing with the GIS is also used for land-use forecasting and modelling (Albhaisi et al., 2013). It is also important to highlight that Landsat is one of the most effective earth observation projects that has benefited the scientific community and the applications of mapping land cover at a resolution of 30 m and detecting changes in land cover (Qiu et al., 2020). Notably, the National Aeronautics and Space Administration (NASA) of the United States launched Landsat in July 1972 to enable continuous and global remote sensing of the earth's resources (Ostensen, 2000).

The satellite data is used for land mapping and has relatively high spatial resolution with a 35-year data record (Knorn et al., 2009). Furthermore, the program has a dataset used to identify those areas undergoing rapid land-cover changes and should be further delineated using fine-resolution observation (Shunlin et al., 2012). Two techniques used for image classification are supervised and unsupervised. Techniques such as supervised classification are normally used in land cover classification and involve the sorting of pixels of unknown identity using a sorting/classification algorithm by means of the spectrum physiognomies of pixels of known information class (Enderle et al., 2005). The un-supervised classification technique, on the other hand, entails selecting an algorithm that uses a collection of remotely sensed data to identify a certain number of statistical bands in multispectral space (Mohd Hasmadi et al., 2009). Post-classification, also known as bi-temporal change detection, is a simple method for identifying LULC changes that entails comparing the extent and regions of LULC classifications across two periods or points in time (Chen et al., 2012; Serra et al., 2003; Wu et al., 2017).

2.5 Hydrological modelling

Worldwide, hydrological models are used for the planning and development of water resources (Singh & Woolhiser, 2003; Byakod et al., 2017). Although most models are deterministic, some of them also include several stochastic elements (Devia et al.,

2015). In other words, according to Vansteenkiste et al. (2011), hydrological models can be either stochastic or deterministic. That being the case, deterministic models are associated with a simulation that generates one possible outcome coupled with one set of parameter values and inputs (Devia et al., 2015). On the other hand, stochastic models have uncertainties in terms of parameter values and inputs, and they allow random-based outcomes (Vansteenkiste et al., 2011; Beven, 2019). Notably, lumped hydrologic models and distribution models are found within deterministic models. In that regard, distribution models, which incorporate the spatial erraticism of inputs and model parameters, contain a more accurate portrayal of the hydrologic system than lumped hydrologic models do (Chow et al., 1988; Pandi et al., 2021).

Additionally, catchment water progressions are frequently shown in tandem with hydrological model classifications (Vansteenkiste et al., 2012). Accordingly, the hydrologic models assist in understanding how land management methods affect the quantity and quality of infiltration, subsurface flow, and deep percolation (Petersen et al., 2017). It should be emphasised that changing the catchment's land use patterns has the potential to change the catchment's natural hydrologic conditions as well (Kabanda & Palamuleni, 2013). Simulation models have been adopted to assist the planning managers as a method for evaluating water resources management strategies to address these problems with land changes and climate change in water resource management (Pandi et al., 2021).

The Water Resources Simulation Model (WRSMPitman), the Agricultural Catchments Research Unit (ACRU), the SWAT model, the Hydrologiska Byråns Vattenavdelning (HBV) model, and the Precipitation Runoff Modelling System (PRMS) are some of the commonly used hydrological models with different limitations and capabilities (Beven, 2019). These physically based models can be used for managing water resources. According to Devia et al. (2015), the choice of a model for a given application is highly influenced by the study's objectives, the data's accessibility, the calibre of its prior research findings, and its usability.

2.5.1 Water Resources Simulation Model (WRSMPitman)

WRSMP was developed in 1973 at the University of Witwatersrand in South Africa by W.V. Pitman as a hydrological model to simulate runoff from both gauged and

ungauged catchments. (Du Plessis & Kalima, 2021; Ndiritu, 2009) . The model has been successfully used for almost 40 years in various parts of the world and has grown to become one of the most popular hydrological models in South Africa. It has been updated recently to reflect the nation's highly developed catchments better (Gush et al., 2002; Hughes, 2013). It has served as the basis for some national water resources development strategies and has been used in a variety of contexts, including research and practical assessments of water resources (Kibii & Du Plessis, 2023). This model has been used from very small to very larger catchments of different complexities in mostly data scarce regions and highly data available areas on a monthly time step (Bailey & Pitman, 2016; Hughes, 2013).

2.5.2 Agricultural Catchment Research Unit (ACRU) model

The Agricultural Catchments Research Unit (ACRU) hydrological model is a physically based semi-distributed, suitable tool for hydrological modelling together with assessing the impact of climate changes on hydrology as well as the impact of land use change in catchments with diverse climates and land uses (Schulze, 2000; Beven, 2019). According to Aduah et al., (2017), the ACRU model uses hydrological response units for the simulation of catchments hydrology and its advantage is being used in a relatively less data-intensive region. The model requires high resolution data, and poor representation of the rainfall (ungagged areas) records pre-processing, and GIS analysis are difficult. The model's inputs are rainfall, temperature (maximum and minimum), land cover, soil properties, catchment characteristics. An extensive soil water budget based on total evaporation forms the basis of the ACRU model's core module (Figure 2.1). The model can simulate the effects of changing land cover and land use on water flows and is sensitive to changes in climate. Using canopy interception losses, total evaporation, and soil water extraction by plant roots, the land use component of the ACRU model is modelled.(Aduah et al., 2017; Chetty & Smithers, 2005)

ACRU - Agrohydrological Model

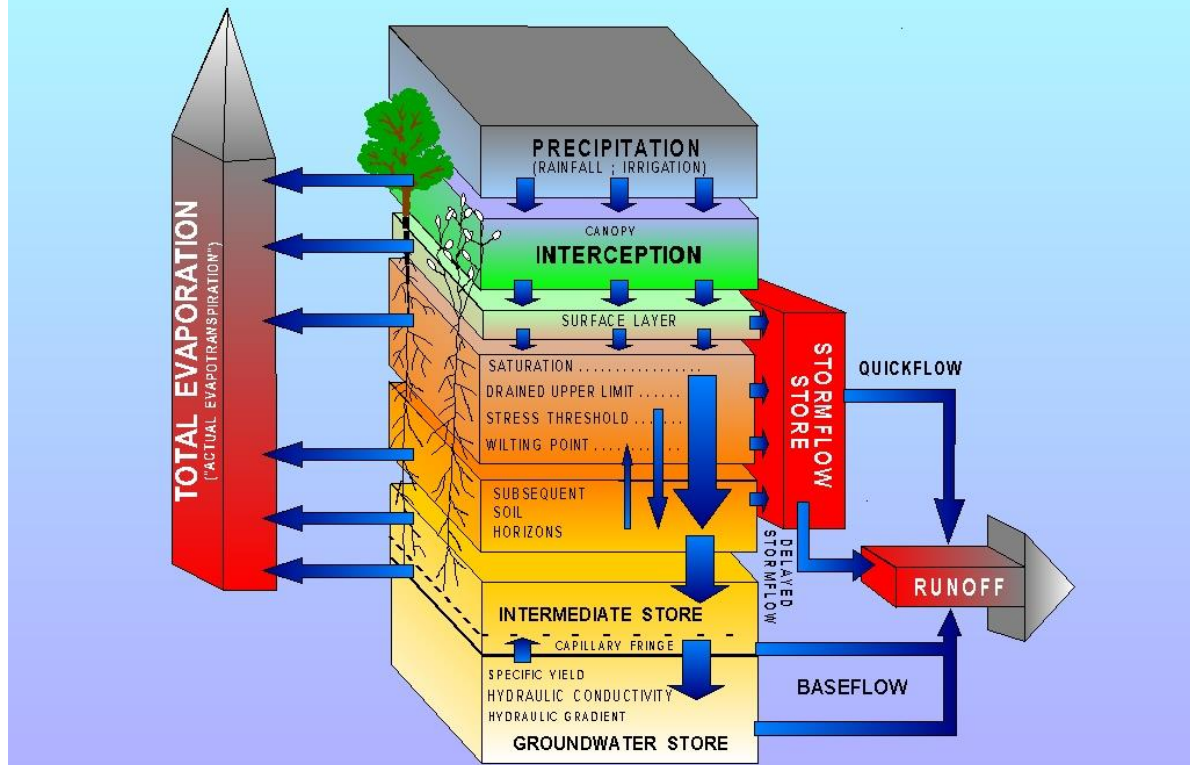


Figure 2.1: Flow diagram of hydrological processes in the ACRU model (Schulze, 1995)

The ACRU model for hydrological modelling in the Bonga catchment was used by Schulze (1995) and Aduah et al. (2017) to assess the suitability of the daily time step. The outcomes demonstrated that the catchment has data drawbacks. This followed the model calibration and careful consideration of sensitivity analysis and parameterisation where initial values were obtained from field observation. It is clear from the latter that the ACRU hydrological model is suitable for comprehending fundamental hydrological responses to climate change and land use in the Bonga catchment and related catchments. Additionally, this model has been widely applied in South Africa for the valuation of water resources (Schulze et al., 1990), management of land use (Kienzle & Schulze, 1992), irrigation supply (Dent, 1988), and evaluation of the impact of LULC on water resources (Smithers et al., 1995; Schulze, 2000), as well as evaluation of the effects of the changing climate on water resources (New, 2002).

According to Pandi et al. (2021), the ACURU model can replicate runoff harvesting and can mimic surface and stormflow from impermeable ground surfaces after a rainstorm event. De Winnaar and Jewitt (2010) investigated the ecohydrological dynamics of runoff harvesting in the Thukela River basin's headwaters with the goal of determining the impact of widespread runoff harvesting deployment on downstream flow regimes. The findings showed that rainfall harvesting had a significant impact on river flow regimes (Devia et al., 2015).

Beven (2019) used the daily-step process-based ACURU model to examine the potential effects of urbanisation on hydrological resource flows within the Umgeni catchment. The study discovered significant relationships between urbanisation and the response of hydrological resources to flow, including intensifications in stormflows, regulated baseflow, and impacts that vary depending on the season and whether it is rainy or dry. Again, due to changes in the rainfall to runoff conversion, the implications of urban hydrology in the same watershed were shown to be severe, especially in humid and desert places (Schütte & Schulze, 2017).

Everson (2001) used the ACURU model where the measurements of the daily actual streamflow, evaporation, rainfall, and soil water storage were recorded for a two-year period in a 97-ha grassland catchment situated in the Natal Drakensberg. The results showed that the empirical 'crop factor' method used to guesstimate the definite evaporation in the model had a remarkable concordance with the Bowen ratio derivative estimated. However, one limitation of the model which became apparent was the incapability to account for subsurface soil water flow in a catchment.

2.5.3 Soil and Water Assessment Tool (SWAT) model

SWAT is a continuous, watershed-scale, physically based distributed parameter hydrological model (Arnold et al., 1998; Cooper, 2010; Zhang et al., 2014). It is a semi-distributed model that may run for longer period of time using daily steps data in both small and large catchments (Arnold et al., 1998; Yira et al., 2016; Zhang et al., 2014). The SWAT model uses the topographic data to divide the catchment into sub-basin (sub-catchment) and then the sub-basin are further divided into hydrological response units (HRUs) with unique combination of land use, soil characteristics and slope types (Arnold et al., 1998; Bhatu & Rank, 2017; Calhoun & Gonzalez, 2005;

Gassman et al., 2007). Figure 2.2 illustrates SWAT model inputs data needed for simulation and the processes involved.

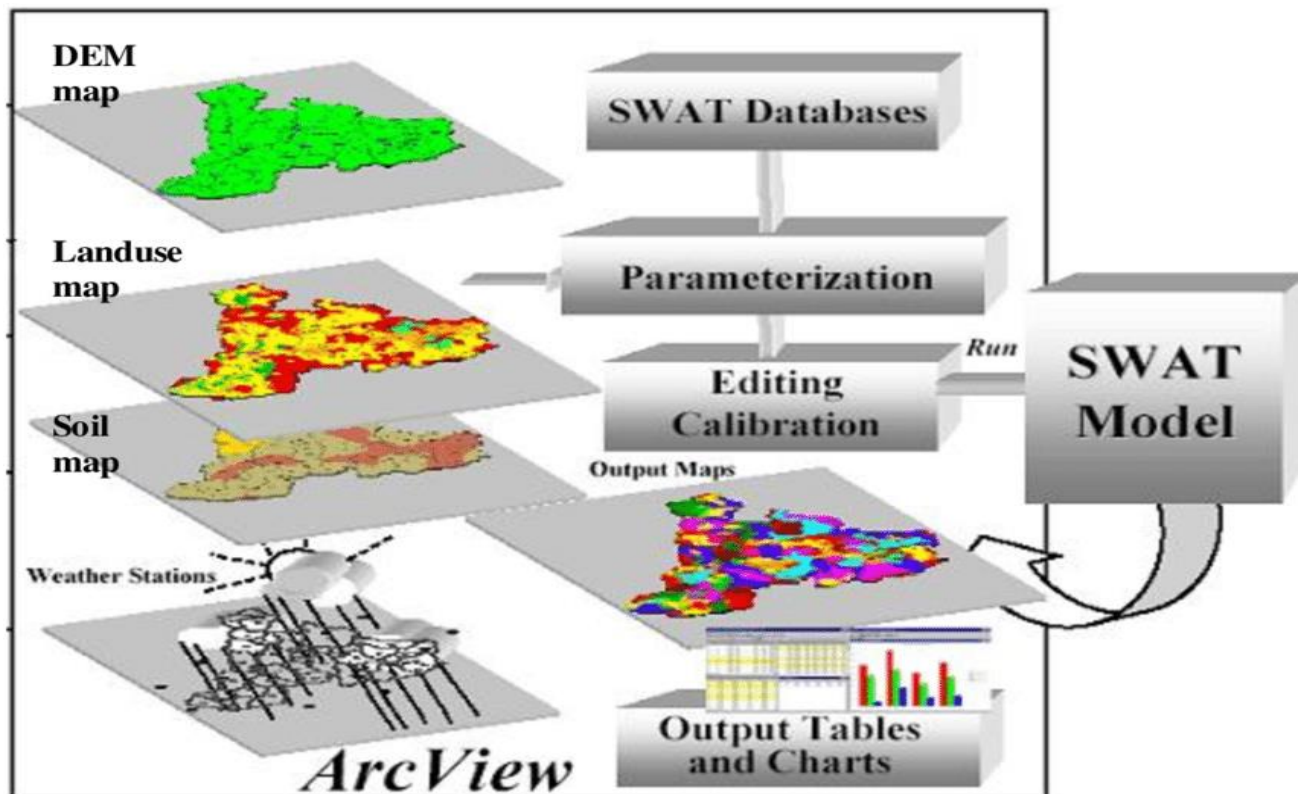


Figure 2.2: SWAT Model input data (thompson, 2015)

The primary source of information for hydrological modelling is weather data. However, the weather data that are currently available for use in hydrological models like the SWAT frequently have gaps in their spatial coverage. To overcome this restriction, SWAT has a build-in weather generator module (WGEN) that can fill in missing weather data and simulate weather parameters for which observed data are not available because in most cases observed weather data are often inadequate with regards to completeness, length, and spatial coverage which accounts for the need to use WGEN that solves this problem by generating data with the same statistical properties as the observed data (Senent-Aparicio et al., 2021). The weather data includes precipitation, maximum and minimum temperatures, wind speed, solar radiation, and relative humidity. Acquiring and analysing meteorological data for hydrological modelling is a laborious and error-prone process so WGEN comes in handy. SWAT's hydrological cycle simulation is predicated on the water balance (Juma et al., 2022). Equation No. 1 below is used to simulate water balance for each HRU (Arnold et al., 1998):

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

Where: SW_t is the final soil water content (mm water), SW_o is the initial soil water content in day i (mm water), t is the time (days), R_{day} is the amount of precipitation in day i (mm water), Q_{surf} is the amount of surface runoff in day i in (mm water), E_a is the amount of evapotranspiration in day i in (mm water), W_{seep} is the amount of water entering the vadose zone from the soil profile in day i in (mm water), Q_{gw} is the amount of return flow in day i (mm water).

Two methods are used to calculate surface runoff namely Soil Conservation Service - curve number (SCS-CN) method (Adeogun et al., 2014; Setegn et al., 2008) and the Green-Ampt infiltration method (Green and Ampt, 1911), using daily rainfall. The U.S. Department of Agriculture's Soil Conservation Service (SCS) (1956), now known as the Natural Resources Conservation Service, created the technique that is now known as the SCS-curve number method for calculating the amount of storm runoff while accounting for abstractions. While its original purpose was to simulate daily runoff influenced by land-use practices, it has also been applied to infiltration and runoff hydrograph modelling for continuous hydrologic simulation (Singh & Woolhiser, 2003). Equation No. 2 for SCS-CN method is below:

$$Q_{surf} = \frac{(R_{day} - I_a)}{(R_{day} - I_a + S)} \quad (2)$$

Where Q_{surf} is the accumulated runoff (mm), R_{day} is the rainfall depth for the day (mm), I_a is the initial abstractions including surface storage, interception, and infiltration prior to runoff (mm), and S is the retention parameter (mm). The value of S differs spatially based on the land use, soil, management, and slope, and can be estimated by Equation No. 3 below:

$$S = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (3)$$

Where CN is the curve number for the day. The initial abstraction, I_a is commonly approximated as $0.2S$, and the SCS-CN equation becomes Equation No. 4 below:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \quad (4)$$

The permeability of the soil, land cover and use, and antecedent soil water all affect the SCS-CN. As a result, it is dependent upon the hydrologic group of the soil, soil

water conditions, and even slope class adjustments. The detailed procedure of determining the SCS-CN refer to Neitsch *et al.*, (2011).

SWAT has options to estimate the potential evapotranspiration (PET) by different methods such as modified Penman–Monteith (Aghsaei *et al.*, 2020; Ritzema, 1994), Hargreaves which requires radiation and temperature (minimum and maximum). This method is tested and found to be providing a better fit of measured data in nearly all cases (Hargreaves & Samani, 1985), and Priestley–Taylor where relative humidity is required when using this method (De Bruin & Keijman, 1979). Given the limited availability of climate variables from the model and, using the WGEN to our advantage for this study to use the Penman-Monteith, this method required relative humidity and solar radiation. Nonetheless, the SWAT model has demonstrated consistent results when calibrated and validated over the reference period using Penman-Monteith method using Equation No. 5 below (Aghsaei *et al.*, 2020).

$$ET = c \left[\frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} 2.7 f(u)(e_a - e_d) \right] \quad (5)$$

ET is evapotranspiration rate (mm/day), c is the adjustment factor (-), Δ is the open water evaporation (kg/m² s), γ psychrometric constant (kPa/°C), $f(u)$ is the wind function where; $f(u) = 1 + 0.864 u_2$, $e_a - e_d$ is the vapour pressure deficit (kPa).

Major model components include weather, hydrology, soil, temperature, plant growth, nutrients, pesticides, and land management (Schilling *et al.*, 2008). The SWAT model has GIS capabilities to handle inputs with high spatial resolution, and physically based simulation capabilities with high temporal resolution to simulate physical processes such as hydrology, soil water interaction, and crop growth on a daily basis (Calhoun & Gonzalez, 2005).

The Muskingum River routing method or the Variable Storage Routing (VSR) method are used to route water flow through the channel network (Rostamian *et al.*, 2008). The shallow aquifer storage component is routed to the stream to simulate the groundwater flow contribution to the overall streamflow. The variable storage routing method is used to simulate channel runoff routing (Mengistu *et al.*, 2021). The VSR method was used to model channel water in this study due to it being used worldwide and providing great results (Olofintoye *et al.*, 2022).

SWAT model has been widely applied in a wide spectrum of areas related to water resources management, such as assessing land use and climate change (Cooper, 2010; Merwade et al., 2017; Zhang et al., 2014). For example, the model has been used to evaluate impacts of land use/cover changes on water balance in China (Liu et al., 2023), West Africa (Awotwi et al., 2015), and also evaluate the impact of future climate and land use/cover change on water resources (Hyandye et al., 2018). However, according to Akoko et al., (2021) the model has proven its effectiveness and reliable performance in other continents, its application results in Africa have high uncertainty.

Aleman et al. (2016) assert that considering the foregoing, SWAT's benefit is in its capacity to apply complex soil water dynamics, which enables extremely extensive inputs concerning agricultural management. On the other hand, according to Rumph Frederiksen and Molina-Navarro (2021), the SWAT has many flaws, like the simulation of the groundwater element. As a result, when simulating lowland regions with reedy unsaturated zones and strong groundwater impacts on streamflow, the SWAT follows a lumped direct reservoir slant, which can lead to modelling errors (Rumph Frederiksen & Molina-Navarro, 2021). Given the extent of existing knowledge and the fact that the SWAT model is still in use in South Africa for the management of water resources, it was chosen for this study. (Gibson et al., 2018; Mengistu et al., 2019)

Bailey et al., (2021) evaluated the contribution of subsurface drainage to watershed of water yield using SWAT+ with groundwater modelling. The results indicated that surface runoff and soil percolation parameters have the strongest effects on watershed-wide subsurface drainage rather than aquifer and drain properties, pointing to a holistic watershed approach to manage subsurface. Notably, the model showed that it can be used to simulate significant hydrologic fluxes in artificially drained watersheds worldwide (Yamini Priya & Manjula, 2020).

2.5.4 Hydrologiska Byrans Vattenavdelning (HBV) model

The HBV is a conceptual model that uses simpler, physically logical algorithms to represent the physical processes and has been applied all over the world (Ashagrie et al., 2006; Hundecha & Bárdossy, 2004; Singh & Woolhiser, 2003). This model was created at the Swedish Meteorological and Hydrological Institute and was among the

first to incorporate the variability parameter into the soil moisture procedure in hydrological models (Bergström et al., 2001). Calibration is used to determine the model parameters, primarily using observed runoff. The catchments that the model is run for are broken down into smaller sub-units with varying land use, temperature, and precipitation characteristics (Johansson et al., 2003). Initially, the HBV hydrological model was developed with the express purpose of simulating runoff within or not too far outside of its calibration range. Its current applications include prediction in ungauged basins as well as use outside of its calibration range (Bergström, 2006). Despite the introduction of area-elevation zoning in its snow routine, the model has been lumped thus far. Over the course of its more than 30-year existence, it has undergone minor improvements, but its original basic structure has not changed (Bergström, 2006).

The snowpack in the HBV model is derived from interpolated daily temperature and point precipitation observations. The highest precipitation occurs at high altitudes, which are rarely visited and challenging to reach, making it challenging to obtain representative data (Johansson et al., 2003). The model can use future climate as an input to a calibrated HBV model to provide future availability of water resources in the catchment and can also be used in a catchment with limited data (Shagega et al., 2020).

2.5.5 Precipitation Runoff Modelling Systems (PRMS) model

PRMS is a distributed-parameter, physical-process hydrologic model that is deterministic and used to simulate and assess how different combinations of land use and climate will affect watershed response (Regan et al., 2018). When PRMS was initially created, it was one single FORTRAN 77 programme made up of subroutine-encoded algorithms that each represented a different physical process in the hydrologic cycle (Regan & LaFontaine, 2017). To assess changes in water-balance relations, streamflow regimes, soil moisture relations, and groundwater recharge, responses to typical and extreme rainfall and snowmelt can be simulated. An algorithm based on a physical law or an empirical relation with measured or estimated characteristics represents each hydrologic process in PRMS (Leavesley et al., 1981).

The daily time-series values of precipitation, minimum and maximum air temperatures, and short-wave solar radiation are inputs into the hydrologic model. If the user does not supply daily short-wave solar radiation, the model can estimate it internal (Legesse et al., 2010). Vegetative canopy interception reduces precipitation that falls as rain, snow, or a combination of the two; precipitation that is not intercepted by the canopy becomes the net precipitation through fall that reaches the watershed surface (Regan et al., 2018). The processes of evaporation, transpiration, sublimation, and snowmelt are propelled by the energy inputs of solar radiation and air temperature. However, the model doesn't take lakes and wetlands into account (Legesse et al., 2010).

A source code with better stability and reliability, enhanced maintainability and supportability, and self-generated documentation can be integrated with other models more readily, like the USGS coupled Groundwater and Surface-water FLOW model (GSFLOW)(Markstrom et al., 2008). Furthermore, every effort has been made to guarantee that the simulation outcomes of PRMS-IV (updated version) are equivalent to those of earlier iterations of PRMS; nonetheless, differences may arise between the computations performed by PRMS-IV and earlier iterations of the code due to bug fixes, updated algorithms, and changing model structure (Leavesley et al., 1981). Table 2.1 summarises the advantages and disadvantages of the five physically based hydrological models.

Table 2.1: Physically based hydrological models summary.

Hydrological Model	Advantages	Disadvantages
Agricultural Catchment Research Unit (ACRU)	• Uses relatively less data-intensive region, • Used in data limited areas. • Applied as a point, lumped or distributed model.	• It is not user-friendly which requires a model expert to fully run it. • Data pre-processing and GIS analysis are difficult. • Incapability to account for subsurface soil water flow in a catchment
Water Resources Simulation Model (WRSMP/Pitman)	• Applied for over 40 years in the world and South Africa	• Insufficient rainfall data results in discrepancies of the model output
Soil and Water Assessment Tool (SWAT) model	• Inbuilt weather generator to simulate missing weather information. • Daily/ monthly and yearly time step • Auto-calibration as an option which reduces labour and uncertainties. • Well adopted using remotely sensed data • Freely accessible	• Assumes the size of the catchment stays unchanged. • Flaws in the simulation of groundwater elements
Precipitation Runoff Modelling Systems (PRMS) model	• simulation outcomes of PRMS-IV (updated version) are equivalent to those of earlier iterations of PRMS • Can be easily integrated with other models such as GSFLOW.	• differences may arise between the computations performed by PRMS-IV and earlier iterations of the code due to bug fixes, updated algorithms, and changing model structure.
Hydrologiska Byråns Vattenavdelning (HBV) model	• Applied in gauged and ungauged areas. • Can be used in data limited areas.	• Poor model improvements over the years • The model doesn't correctly reproduce all observed big floods.

2.6 Model calibration and validation.

Model calibration involved the estimation of model restrictions by relating experimental data for similar conditions with model outputs for a given set of presumed conditions (Moriasi et al., 2012). Model parameters are calibrated to produce model predictions that are as close as possible to observed data in practical applications (Cooper, 2010). On that note, calibration actions differ amongst models with some only supporting manual calibration, while others support both manual and automatic calibration (Moriasi et al., 1983; Arnold et al., 2012). Model validation is supported by and encouraged by the majority of these models (Moriasi et al., 1995). Model validation, according to Arnold et al. (2012), is the process of running a model with input parameters that were measured or established during the calibration step. In light of the endorsed model evaluation, statistics with conforming performance ratings and suitable graphical analyses (Arnold et al., 2012; Moriasi et al., 2012), broad model validation principles have been acknowledged.

To efficiently and effectively apply the SWAT model, different calibration and uncertainty analysis methods have been developed and applied to improve the prediction reliability and quantify prediction uncertainty of SWAT simulations (Guug et al., 2020; Tamm et al., 2018). Imprecise or spatially interpolated measurements of model input or initial conditions, such as elevation, land use, temperature, intensity of rainfall, and initial groundwater levels, are frequently linked to input uncertainty (Yang et al., 2008). Due to the large number of unknown parameters and errors in the data used for parameter calibration, distributed models may also have additional uncertainties (Gassman et al., 2007). Over the past 20 years, numerous uncertainty-analysis techniques have been developed and applied to different catchments to account for these uncertainties (Yang et al., 2008). To account for such uncertainties, researchers have developed a variety of uncertainty analysis techniques, including the sequential uncertainty fitting version 2 (SUFI-2) (Abbaspour et al., 2007), the parameter solution (ParaSol) (Setegn et al., 2008; Sharma et al., 2022), the generalised likelihood uncertainty estimation (GLUE) (Sharma et al., 2022), and the Markov chain Monte Carlo (MCMC) method (Yang et al., 2008). SWAT calibration uncertainty procedure (SWAT-CUP) is a package that combines these techniques with SWAT (Rostamian et al., 2008). Abbaspour *et al.*, (2007) created the freeware programme SWAT-CUP, which is the main domain and enables the optimisation of

the SWAT model using the various algorithms (SUFI-2, GLUE, MCMC, and ParaSol). This makes it possible to do uncertainty analysis, calibration, validation, and sensitivity analysis while focusing on the relevant variable (streamflow, for example).

SUFI-2 defines uncertainty as the difference between the variables that are simulated and those that are measured (Rostamian et al., 2008). Therefore, we must include all the measured data aside from the outliers in the prediction uncertainty to account for this uncertainty. To identify parameter uncertainties that produce prediction uncertainties that bracket most of the measured data while generating the smallest possible prediction uncertainty band, SUFI-2 combines calibration and uncertainty analysis (Rufino et al., 2022). Therefore, the uncertainties in the parameter represent all possible sources of uncertainty: the conceptual model, forcing inputs (like rainfall), and the parameter itself. The model output uncertainty in SUFI-2 is measured at the 95% prediction uncertainty (95PPU) determined between 2.5% and 97.5% levels of the cumulative distribution using Latin hypercube sampling, whereas the input parameter uncertainty is represented as a uniform distribution (Kouchi et al., 2017).

The SUFI-2 model takes a large initial assumption for the parameter uncertainty (within a physically meaningful range) to initially place the measured data within the 95PPU (Rostamian, 2010). It then gradually reduces this uncertainty while keeping an eye on the P and D factors. In light of the above, P-factor is a measure of the percentage of observed streamflow that the 95PPU can encompass (Moriassi et al., 1983). A P-factor = 1 indicates that all the observations are bracketed by the 95PPU band (Arnold et al., 2012). The 95PPU band's thickness is measured by the R-factor and it calculates the ratio of the observed streamflow's standard deviation to the 95PPU's average width (Moriassi et al., 2012). A P-factor > 0.70 and R-factor of 1.5 indicate that a prediction's uncertainty is acceptable (Mtibaa & Asano, 2022). Pearson's correlation coefficient (r) and coefficient of determination (R^2) reveal the degree of collinearity between measured and simulated data (Moriassi et al., 2012). R^2 is a measure of how much of the variance in the measured data the model can explain. R^2 spans from 0 to 1, with 0 denoting no correlation and 1 denoting perfect correlation, and it provides an evaluation of how accurately the variance of experimental data is simulated after model projections (Arnold et al., 2012). Table 2.2 provides the acceptable level and threshold evaluation for the various calibration and validation.

Table 2.2: General performance ratings for recommended statistics for a monthly time step

Performance Rating	RSR	NSE	PBIAS (%) (Streamflow)
Very good	0 – 0.50	0.75 -1.00	<±10
Good	0.50 – 0.60	0.65 - 0.75	±10 - ±15
Satisfactory	0.60 – 0.70	0.50 - 0.65	±15 - ±25
Unsatisfactory	>0.70	≤0.5	≥±25

Source: (Moriassi et al., 2007; Daggupati et al., 2015)

2.7 Chapter Summary

This chapter focused on the literature which was reviewed in agreement with the objectives of the study. The reviewed literature addressed the following concepts: an overview of land-use scenarios, impacts of LULC changes on water balance, and impacts of climate change on water resources. Furthermore, the literature review chapter focused on detecting the change in LULC using satellite data/imagery, hydrological model using SWAT and model calibration and validation that are used for streamflow analysis. The next chapter focuses on the materials and methods used in the study.

CHAPTER 3: DESCRIPTION OF THE STUDY AREA

3.1 Introduction

The study area is the C81F quaternary catchment located in the Eastern Free State, under the Thabo Mofutsanyane District Municipality. The municipality lies between latitude -27.945 and 28.783 longitude. It is a semi-arid region with a dispersed habitation pattern that covers a catchment area of 67665.240 hectares (ha), as presented in Figure 3.1. The catchment has an average annual rainfall of 690 mm, with minimum temperatures of 1.0°C occurring in July, and maximum temperatures of 26.5°C occurring in December. Water Resources (WR) 2012 recorded that the naturalised flow of 89.8, 108.38, 109.55 in million cubic meters for WR90, WR2005 and WR2012 respectively. The mean annual evaporation is recorded as 1300 mm where S-pan method is used for WR2012. The catchment is situated within the Vaal and Orange River basins which are also water management areas with common climate and hydrological characteristics. The catchment has the highest percentage of clay-loam soil texture which is suitable for conservation (Figure 3.3). The catchment elevations are between 1614 and 3274 above mean sea level (Figure 3.2).

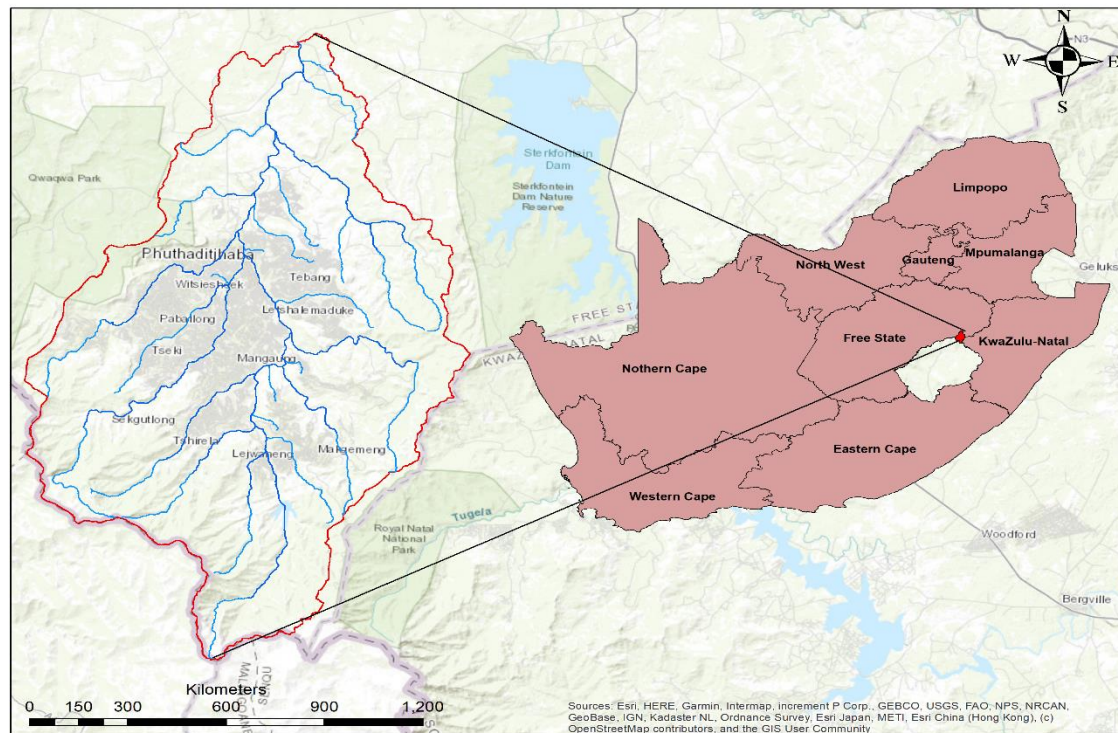


Figure 3.1: Location map of C81F quaternary catchment

The digital elevation model (DEM) is sourced from earth explorer sampled to the resolution of 30 m x 30m.

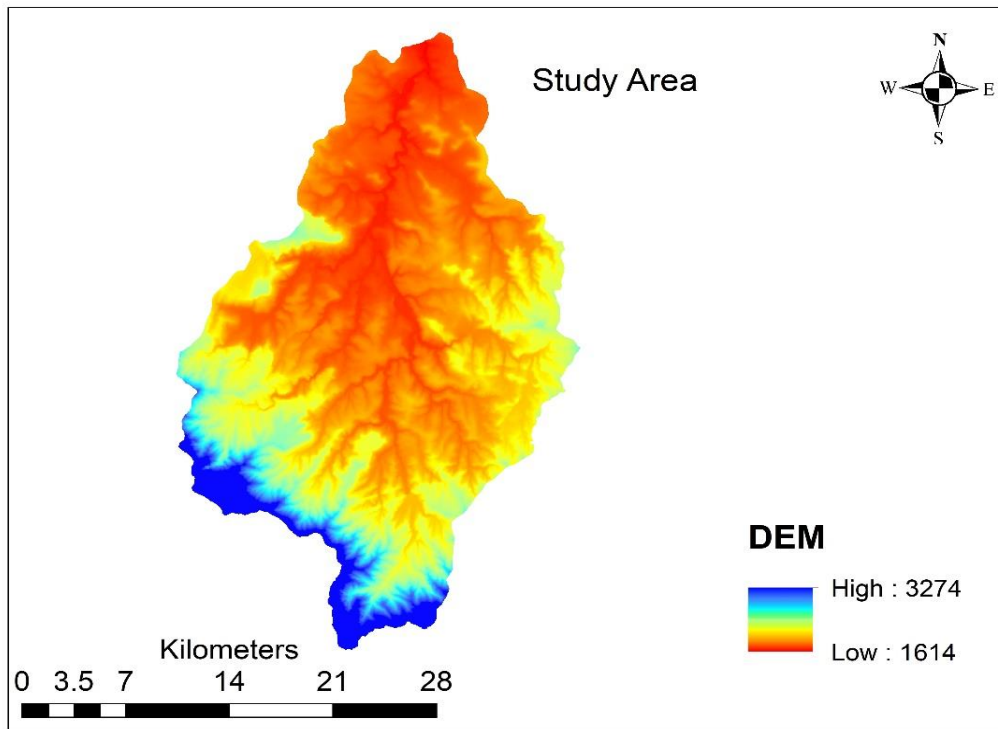


Figure 3.2: The digital elevation model of C81F quaternary catchment.

The houses are scattered, and the impact of low rainfall in the Free State province has contributed to the low average water levels in dams. Thus, the municipality is currently experiencing water scarcity with poor quality. The problem has been exacerbated by drought, reduced runoff, and increased evaporation which continues to be experienced by this region (LGCCSP, 2016). The catchment has four flow gauging station with available daily and monthly data sourced from the Department of Water and Sanitation (Table 3.1).

Table 3.1 Flow gauging stations

Gauging station	Latitude	Longitude	River
C8H003	-27.84500	28.96222	Cornelius
C8H005	-28.37583	28.86027	Elands
C8H023	-28.02305	28.99472	Meul
C8H028	-27.80277	28.76750	Wilgel

3.2 Soil

Soil is essential to the agriculture sector. The catchment has three soil properties, with clay-loam as the highest followed by loam and clay, respectively. The capacity of soil to support human health and habitation, produce plants and animals, improve, or maintain the quality of air, and operate within managed or unmanaged ecological constraints is referred to as its soil quality. The quality of the soil reflects the state of its capacity to perform within a specific environmental setting (Pulido-Moncada et al., 2015). The geology of the study area includes sediment rocks from the intercalated arenaceous and argillaceous strata which is mainly clay minerals, Figure 3.3 illustrates the soil distribution across the basin. The soil data for this study was sourced from FAO-UNESCO global soil map at 5 kilometres resolution.

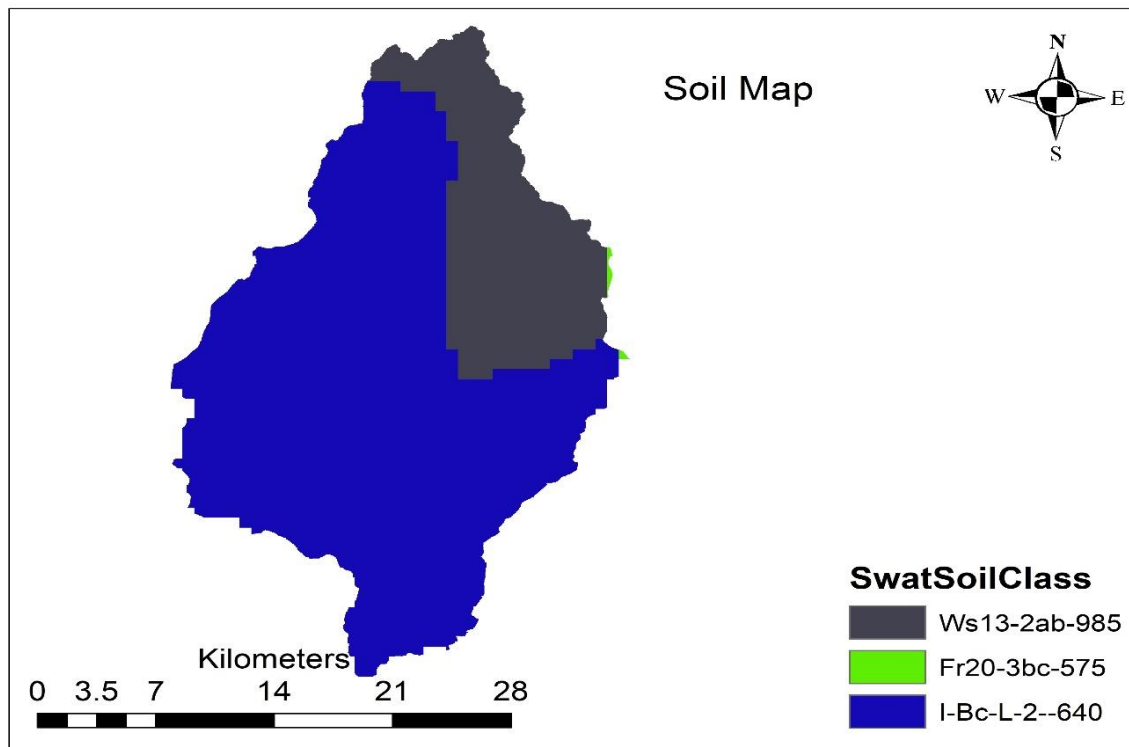


Figure 3.1: The created Soil Map for the catchment

3.3 Climate

There are four weather stations in the study area (Table 3.2). The weather stations are shown in Table 3.2 of study area which have direct impact on the catchment. The van reen station data is sourced from South African Weather Services (SAWS), where witsiehoek, kestell-pol and Harrismith-Tnk were sourced from the Agricultural

Research Council (ARC). The data set available before 2000 used mechanical stations whereby in the year 2000 the automatic stations were operating (Moeletsi et al., 2022). The four stations had rainfall data and temperature data but no solar radiation, wind speed and relative humidity. The rainfall and temperature data still had some gaps with missing data for some years. The gaps in the weather data were addressed by using the WGEN tool which were generated. The mean annual rainfall experienced in the study area is 690 mm, where the lowest temperatures was experienced in July with 1.0°C occurring in July, and maximum temperatures of 26.5°C occurring in December.

The main challenge is erratic rainfall patterns leading to changes in cropping systems and reduced hectares. This has resulted in high stress levels among most farmers with some reportedly committing suicide because of mental breakdowns caused by bank closures and the impact on their lives (Agri-SA, 2019). Climate change is badly affecting agricultural activities, and due to the exceptionally high atmospheric demand, evaporative losses in South Africa are already significant ranging from 1400 mm to 3000 mm per year (Botai et al., 2016), where the WR90 recorded that C81F quaternary catchment experiences the evaporation of 1200 mm to 1400 mm. In this regard, semi-arid environments are frequently caused by high evaporative losses paired with unpredictable rainfall. This is true in some cases even when there is enough rainfall (Mpandeli et al., 2017). Evapotranspiration from crops, which is combined with evaporation, is used to calculate how much water a crop needs. An analysis to determine sensitivity shows that a 2°C temperature increase in the summer (January) will trigger an increase in crop evapotranspiration of 3.5%, whereas the proportion is larger in the winter (Mbileni, 2015).

Table 3.2 Rainfall stations

Climate Number	Station Name	Latitude	Longitude
0298512 6	Witsieshoek	-28.53	28.80
0332349 7	Kestell-Pol	-28.32	28.70
0333226 5	Harrismith-Tnk	-28.27	29.13
0333682A 9	Van Reenen	-28.37	29.38

3.4 LULC

The study area has seven LULC classes, which are water, wetlands, mixed forest, pasture, generic agricultural land, barren land and urban. Throughout the 28 years the classes remained the same but changed in area magnitude. Figure 3.4 shows a part of the C81F quaternary catchment where urban imagery was taken from 2018. The government intensified the campaign for communities to engage in agricultural productivity to enhance food security. The agricultural sector also absorbs more labour than other economic sectors. Thabo Mofutsanyana District Municipality also produces 90% of the country's cherry crops. There are many sunflower seed farms in its northern regions a significant centre for sunflower seed production being Tweespruit (Cooperative Governance and Traditional Affairs, 2021).



Figure 3.4: 2018 imagery of a part of the study area

As a result of the variety of land uses and agricultural practices, rural areas offer a wide range of economic options. Nevertheless, because the agriculture industry employs many people in the area, it is important to educate people about the significance of land use. Water availability is essential to the development of the Free State province because of the significant agricultural industry, which generates a significant number of jobs and income, as well as hydropower generation in the Upper Orange watershed and mining (Mbileni, 2015). In addition, tourism is the tertiary economic driver in the district due to its scenic and rich cultural heritage which makes the place to be greenery and beautiful grass. However, the province has seen a decline in biodiversity because of the effects of mining, farming, and urban expansion (Muyambo et al., 2023). The catchment is poised to experience an increase in the prevalence of alien plant species, a rise in atmospheric carbon dioxide levels, and a decrease in the frequency of frost owing to the predicted climate changes (Mocwagae, 2020). This will, in turn, promote tree growth and the savannah biome's encroachment into the already endangered grassland habitat (Cooperative Governance and Traditional Affairs, 2021).

3.5 Chapter Summary

This chapter described the study area of hydrology. The discussion about the overall information on the catchment was detailed including the soil data, LULC data, weather data (precipitation stations), and flow gauging stations. The next chapter focuses on the materials and methods used in the study.

CHAPTER 4: MATERIALS AND METHODS.

4.1 Introduction

The SWAT model was chosen out of the five hydrological models reviewed under literature for the purpose of this study. The reason for the choice is expressed in Table 2.1, which summarises the advantages and disadvantages of the models. SWAT model has a feature to crucially assess the effects of land use and climate variations in the region which are essential for understanding the complex hydrological processes in the area. The purpose of using SWAT model in this study was to analyse the impact of LULC changes on water balance for the period of 1990 to 2018. Based on previous studies and literature, the model was considered best in simulating water balance components using past data. The model has not been applied in the C81F catchment thus this gives an opportunity to test the model parameters for the area at large. The C81F quaternary catchment was used to test ArcSWAT's effectiveness and efficacy in simulating the hydrological operation of a catchment in South Africa. ArcSWAT version SWAT2012 was adopted to model the C81F quaternary catchment. The research involved collecting data such as observed streamflow, climate, Digital Elevation Model (DEM), soil and land use. The study area has a four-flow gauging and four rainfall gauging stations. The rainfall stations don't include recorded data of solar radiation, wind speed and relative humidity but due to ArcSWAT having WGEN tool to fill the gaps in climate data. A sensitivity analysis was performed to identify sensitive parameters that might have an impact on the simulation results of the model. As a result, the accuracy of the model was calibrated and validated using the SWAT-CUP tool, and the parameters are graded based on how sensitive they are to the model output. The model was then assessed against appropriate standards for the monthly time steps as a final step.

4.2 Classification of LULC

Figure 4.1 depicts a schematic illustration of the data analysis of LULC that was implemented. The South African National Land Cover (SANLC) project data source was used for the period 1990 and 2018 (Thompson, 2019a). The digital satellite image

was utilised to analyse the dynamics of LULC changes from 1990 to 2018 in the C81F catchment captured in South Africa (Thompson, 2019b). The 1990 used Landsat-5 image at 30 m, 2000 and 2010 used 12 May Landsat images of Enhanced Thematic Mapper plus (ETM+) and 2018 used Landsat-8 multi-spectral imagery. The cloud was set to 10% because we don't need cloud cover for LULC data. The USGS (<https://earthexplorer.usgs.gov>) has made these time series of Landsat images, which were taken during the dry seasons, freely available.

LULC types that are already known through a combination of fieldwork, map analysis, and firsthand experience are identified using this type of classification (Thompson, 2015), based on the classification system that the SANLC created to generate different LULC maps of the catchment. Several colour composites were used to enhance the quality of the classes: near infrared and red were used to identify built-up and barren areas, while infrared was used to distinguish between different shades of vegetation. In this study, post-classification refinement was carried out to reduce those errors and further increase the classification accuracy. Therefore, to classify these images of 1990 to 2018, preprocessing and enhancement techniques using ArcGIS were applied before implementing the unsupervised classification scheme.

Semi-automated modelling is a technique used to facilitate the rapid production of consistent, standardised land cover information from Landsat imagery with long-term dataset (Thompson, 2015). Un-supervised classification techniques were used under post-classification, involved the analyst-assisted pixel-based classifiers, were made possible by semi-automated land-cover mapping techniques. This further allowed a rapid production of informative though standardised land-cover information and classification. This enabled the availability of adequate standardised references through which landscape changes could be determined and calculated (Thompson, 2016). To verify the classifications ground truthing was carried out, instead of site visitation, data for LULC classification used high-resolution imagery from Landsat, Google Earth and google map as a reference for visual clarification. Each data cell has a single code that, after the analysis of the multi-date imagery acquired throughout that image frame, represents the dominant land-cover class (by area) within that 30 x 30m unit (Thompson, 2016)

The LULC datasets where semi- automated and spectral modelling procedures were used to generate, derive, and define the basic components such as water, bush,

grassland, bare ground, and water. The LULC maps were generated for 1990 to 2018. In contrast to 2018, which employed Sentinel-2 photos with a 20 m spatial resolution, LULC data for 1990 to 2010 were extracted from Landsat images at a 30 m spatial resolution (Botai et al., 2016). The LULC data for 1990 to 2010, covering the whole of South Africa, was provided in a map-corrected, raster format and is based on 30 m x 30 m cells, similar to the picture resolution of the original data, Landsat 8 multi-spectral photography. The 2018 data images were then resampled at 30 m resolution for compatibility with those of the 1990 LULC. The 2018 raster format was resampled using raster processing under the data management tool in ArcGIS from 20 m to 30 x 30 m pixel size.

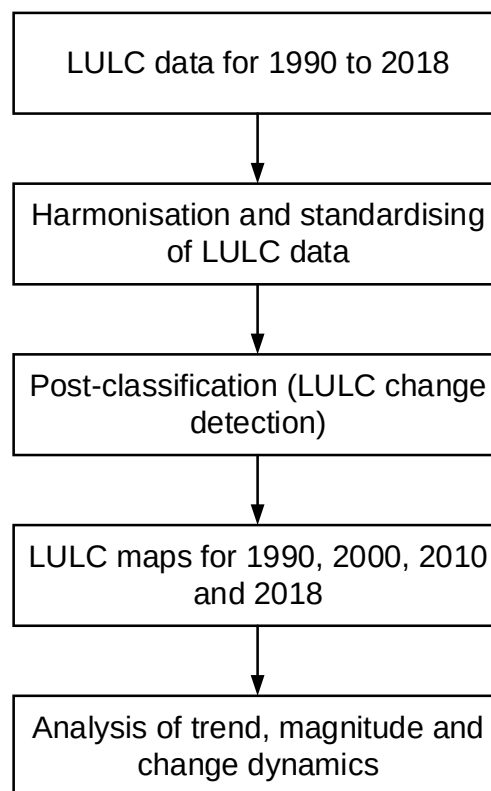


Figure 4.1: Schematic representation of LULC change analysis.

These years were selected to detect the possible change occurring over a long time. Class name reduction is based on the major changes that happened over the years in the catchment area. The legends were harmonised and standardised to enable comparison. Finally, evidence for the study was gathered through ArcGIS mapping and ground truthing. After the LULC legends and maps were harmonised, a post-classification method for LULC changes analysis was completed next.

This provides the path of change throughout various periods. In this study, 1990 and 2018 were used as the comparison years. According to Equation No.6, the area magnitude from the new and prior years was subtracted to estimate the magnitude change for each LULC class (Islam et al., 2018). Equation No. 6 is as follows:

$$\text{Change in Magnitude} = \text{magnitude of the new year} - \text{magnitude of the previous year} \quad (6)$$

The magnitude change formula (adapted from Islam et al., 2018).

It should be noted that the magnitude change was then divided by the base year (the first year), multiplied by 100, and the result was the % change (trend) for each land use category, as indicated in Equation No. 7.

$$\text{Percentage Change} = \frac{\text{Magnitude of Change} * 100}{\text{Base Year}} \quad (7)$$

The variance between the initial and final year which signifies the magnitude of change between matching years was divided by the number of study years, i.e., 1990-2018 (28 years), respectively, using Equation No. 8 to determine the annual rate of change for each land use type 3. The detection change statistics and matrix were generated using a ha/year formula. The rate of change (ha/year) Equation No. 8 described by (Meshesha et al., 2016). Equation No. 8 is as follows:

$$R\Delta \left(\frac{\text{ha}}{\text{year}} \right) = \frac{Z-X}{W} \quad (8)$$

A ha/year formula (adapted from (Meshesha et al., 2016)

The equation value is described as follows: $R\Delta$ = rate of change, Z = recent area of LULC type in ha, X= time interval between Z and W is years. The LULC classes were mapped to suit SWAT model specifications.

4.3 Hydrological Modelling Approach

For hydrologic modelling objectives, the model input parameters were changed, rated, and examined using the proper time steps (yearly, monthly, and daily). The inputs were soil data, DEM, climate data and LULC map. Input data were gathered from multiple sources to meet the requirements of the pre-processing, and modelling program. Hydrometeorological, LULC and hydrological data analysis, as well as pre-processing were executed using various software, such as ArcGIS 10.7.1, GWN, and ArcSWAT version SWAT2012 modelling tool. ArcGIS 10.7.1 offers temporal and

spatial analysis tools which helps to process the hydrology of the catchment. This tool is used to process raw data in a form of a shapefile to a raster map which will be used for modelling, geoprocessing tool, hydrology tool, image classification, extraction and reclassification tool were used in ArcGIS. The LULC data is for 1990 and 2018. The projected coordinate system and geographic coordinate system were WGS_1984 and WGS_1984_UTM_Zone_35S, respectively.

4.4 SWAT Model set up.

Hydrological simulation was performed with the 2012 version of SWAT model through an interface between the model and ArcGIS 10.7.1 software. Model set-up includes three stages. The first stage in ArcSWAT is catchment delineation into sub-basins where the main input data is DEM. The second stage was HRU definition; this is the stage where the LULC map, soil data and slope definition are utilised. The third stage is the application of the default input and weather data definition. This involves setting up of required specification period, prepared rainfall data, temperature (minimum and maximum) data, surface runoff calculations and PET calculation method before running ArcSWAT. The model was run for 28-year period from 1990 to 2018 where the first three-years was a warm-up period were not included in the analysis to achieve a steady state and mitigate unknown initial conditions for SWAT model. SWAT-CUP was utilised to calibrate and validate data using the 2018 LULC. LULC was used as the base, so the recent year was used. Figure 4.2 is showing the process followed in SWAT modelling. For calibration, observed streamflow from 1993 to 2007 was used and the 2008 to 2018 period was used for validation with the same parameters chosen for the last calibration simulation.

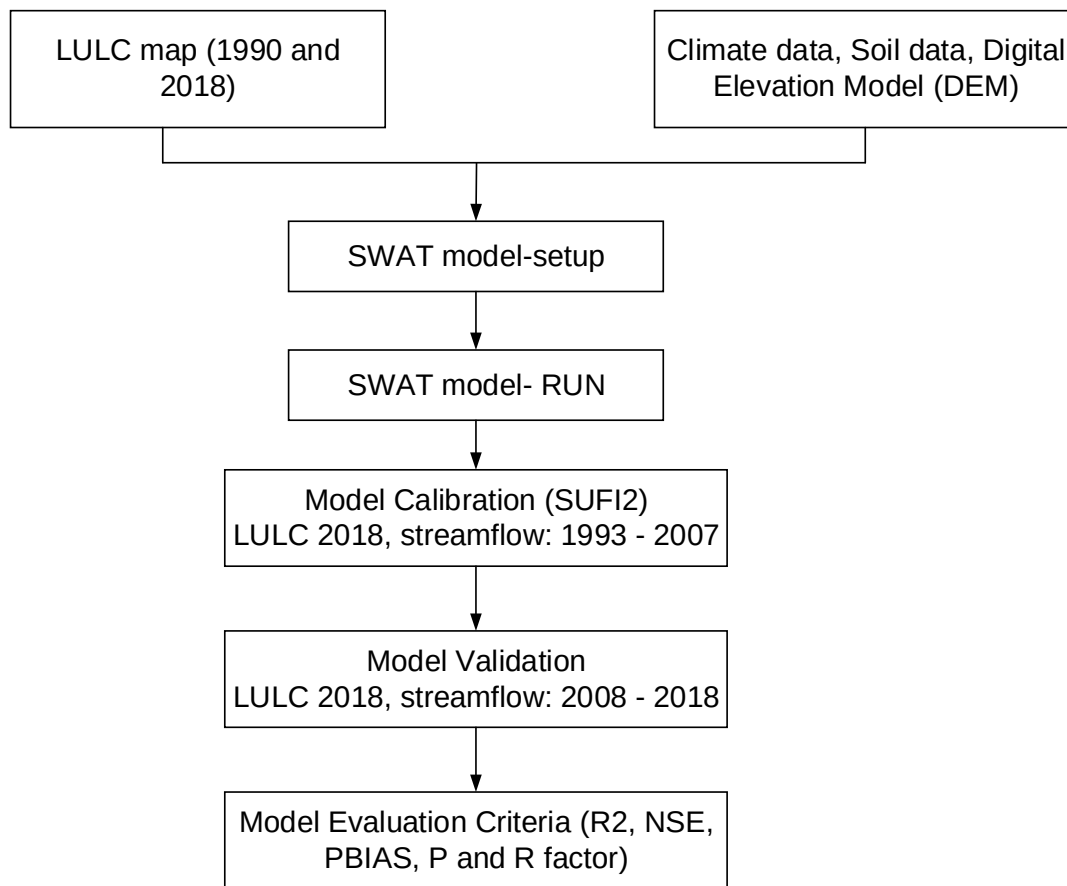


Figure 4.2: Flowchart of SWAT modelling process.

4.4.1 Catchment Delineation

Since the DEM determines all the topographic parameters for HRU's catchment and sub-basin levels, it is a crucial data collection. The DEM is used by ArcSWAT to define hydrological features such as stream flow direction, reservoirs, and ponds. The catchment features are required for the modelling process during the catchment delineation phase, which is the first stage in defining area, channel length, slope, slope length, channel depth, channel slope, and channel width, which are some of the properties. The DEM was prepared using ArcTools. When creating a user database in ArcSWAT, the defined hydrological characteristics may be further characterised and assigned attributes.

The catchment delineation is defined using ArcSWAT's five phases, which comprise DEM setup, sub-basin parameter computation, stream definition, and inlet and outlet definition. The study area DEM was defined in the catchment delineation stage. A catchment (basin) in SWAT is subdivided into sub-basin (sub- catchments), which are further divided into combinations of distinct soil, land use, and management

features known as hydrological response units (HRU) that are connected to the network of rivers. HRUs are non-spatially distributed. Every HRU has its rainfall and evaporation calculated. Sub-basins were automatically delineated using the SWAT tool. Based on topography, flow direction, and flow accumulation, and stream networks were generated. Filling the catchment in the DEM and raising their elevation until they overflow creates a flow vector that is used to delineate the catchment. Flow accumulation is related to the flowing cells, which are a part of the stream network, and is created by numbering the cells flowing into each unit in the grid after the overflow has occurred (Ncube, 2006). Stream networks were automatically generated, and the catchment outlet was added to change it to meet the project's specifications. Sub-basin is computed in the SWAT model as contributing areas to a single stream channel. The catchment with reach, catchment and longest path that was created in the delineation stage. The outlet is situated at the lowest point of the catchment.

Sub-basin characteristics were calculated to complete catchment delineation. The topographic report of the catchment is shown in Appendix A and provides a statistical summary and distribution of distinct land surface elevations in the catchment and its sub-basin.

4.4.2 LULC and Soil Data Layers

The procedure of catchment delineation was followed by the definition of HRUs. On the ArcSWAT interface, the HRUs were defined. 30 x 30 m resolution LULC maps from the years 1990 and 2018 were used. On the other hand, user lookup tables were established to link the ArcSWAT code to the land-use maps. After the catchment had been delineated and subdivided into sub-basins, the next stage in ArcSWAT was to subdivide the basins into HRUs. The procedure necessitates the specification of soil characteristics, land cover/use, and slope analysis. The LULC classifications were and guided by Thompson (2019b) to suit the model's objectives.

Soil is another type of data that has a significant impact on catchment hydrology. The FAO Harmonised global soil database (adapted from <https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/>, accessed from 20 April 2021) was used to download the soil data. The soil data from the African soil slice of the FAO soil database was extracted using the catchment

boundary. Due to the "user soil" table of the ArcSWAT12 soil database only containing USA soils, the qualities of these soils were restructured using a "user soil" table from the Map Window SWAT12 database. The soil properties were mainly sourced from Fey (2010). The LULC and soil maps were projected to WGS_1984_UTM_Zone_35S coordinate system. User lookup tables were developed to link the ArcSWAT code to the soil map.

4.4.3 HRU Definition and Distribution

The catchment delineated was split into many sub-basins that are linked by surface flow in the SWAT modelling technique. The sub-basins are prioritised based on their size. Following that, each sub-basin is further subdivided into clusters of homogeneous land cover/use, soil types, slope, and management practice, which are referred to as Hydrologic Response Units (HRUs). Hydrological components are estimated individually in each HRU, and the results are gathered at the basin outflow. The HRUs are percentages of the sub-basin region and are not geographically identifiable in a SWAT simulation (Gassman et al., 2007). SWAT's HRU analysis incorporates slope class classifications as well as soils and land use. The various slope choices (which comprise several slope classes for HRU definition) were used, with 5 slope classes utilised in increments of 20%. The SWAT model generated the HRUs because it could interpret the data from the maps, soil, and land use tables. The information from slope range, soil, and land use maps and tables was superimposed over analyses of land use, slopes, and soil to create the HRUs.

4.4.4 Weather Data Definition

The daily climate variables of precipitation, temperature, relative humidity, wind speed, and solar energy are included in the obtained meteorological data. ArcSWAT also comes with a weather generator tool that helps us fill in the gaps in the simulation periods' lacking data. If we feed it with long-term daily precipitation rates as well as minimum and maximum temperatures, this tool can also generate solar energy, relative humidity, and wind speed (Neitsch et al., 2009). Notably, the SAWS and ARC contributed immensely to the long-term data details. The necessity for weather generators to address this issue by producing data with similar statistical attributes as the experimental data was because measured weather data are frequently

insufficient in terms of length, completeness, and spatial coverage (Senent-Aparicio et al., 2021). Table 4.1 is the description of all the variables used under the weather definition on ArcSWAT. Climate variables such as rainfall and temperature affect the catchment's water balance, temporal and spatial variability. Lookup table was prepared for rainfall data and temperature (minimum and maximum) to best suit the model input format, the missing data was then calculated by WGEN for relative humidity, solar radiation, and wind speed. To start, WGEN calculates the precipitation for the day on its own. The amount of precipitation is calculated using an exponential or skewed distribution for each wet day. Then, depending on whether or not it will rain during the day, the maximum and lowest temperatures, solar radiation, and relative humidity are calculated. The wind speed is produced independently. The SWAT theoretical documentation contains details on WGEN equations (Neitsch et al., 2011).

Table 4.1: Table of user Weather Generator elements

Name	Definition
Station ID	Station name and coordinates
Rain_Yrs	Number of years used to determine values for precipitation parameters
TMPMX	Average maximum air temperature in a month in °C (Jan to Dec)
TMPMN	Average minimum air temperature in a month in °C (Jan to Dec)
TMPSTDMX	The standard deviation of maximum air temperature in a month in °C (Jan to Dec)
TMPSTDMN	Standard deviation of minimum air temperature in a month in °C (Jan to Dec)
PCPMN	Average precipitation in a month (mm/day)
PCPSTD	Standard deviation for daily precipitation in a month (mm/day)
PCPSKW	Skew coefficient for daily precipitation in a month (mm/day)
PR_W1	Probability of a wet day following dry day in a month
PR_W2	Probability of a wet day following wet day in a month
PCPD	Average number of days of precipitation in a month
RAINHHMX	Maximum 0.5 h rainfall in a month for the entire period of record (mm)
DEWPT	Average dew point temperature in a month (°C)
SOLARAV	Average daily solar radiation in a month (MJ/m ² /day)
WINDAV (optional)	Average daily wind speed in a month (m/s)

This study employed the SCS-CN method to estimate the rainfall runoff process., based on the available data of local land use, soil type, and antecedent moisture conditions to calculate surface runoff. Also, the Penman-Monteith equation was utilised to estimate potential evapotranspiration, and the Variable Storage Routing (VSR) was used to model channel water routing. The SWAT simulation was

completed once all the preceding stages were accomplished. The duration of the simulation (including the warm-up periods) was set from 1990 to 2018.

4.5. Model Calibration and Validation

SWAT-CUP version 2012 (the SWAT uncertainty and calibration programs) was used to calibrate and validate where the monthly streamflow data was used as an input (observed flow data). The outlet's gauging station was used for calibration and validation. One of the stochastic calibration algorithms in SWAT-CUP used in this study was the Sequential Uncertainty Fitting version 2 (SUF12). The simulated ArcSWAT project (text file) is used to create a new SWAT-CUP project, where the SUF12 program was used. Calibration parameters were selected for the catchment and the minimum and maximum values on each parameter were selected guided by the sensitivity of each of the catchment characteristics. Figure 4.3 illustrates the procedure that was followed.

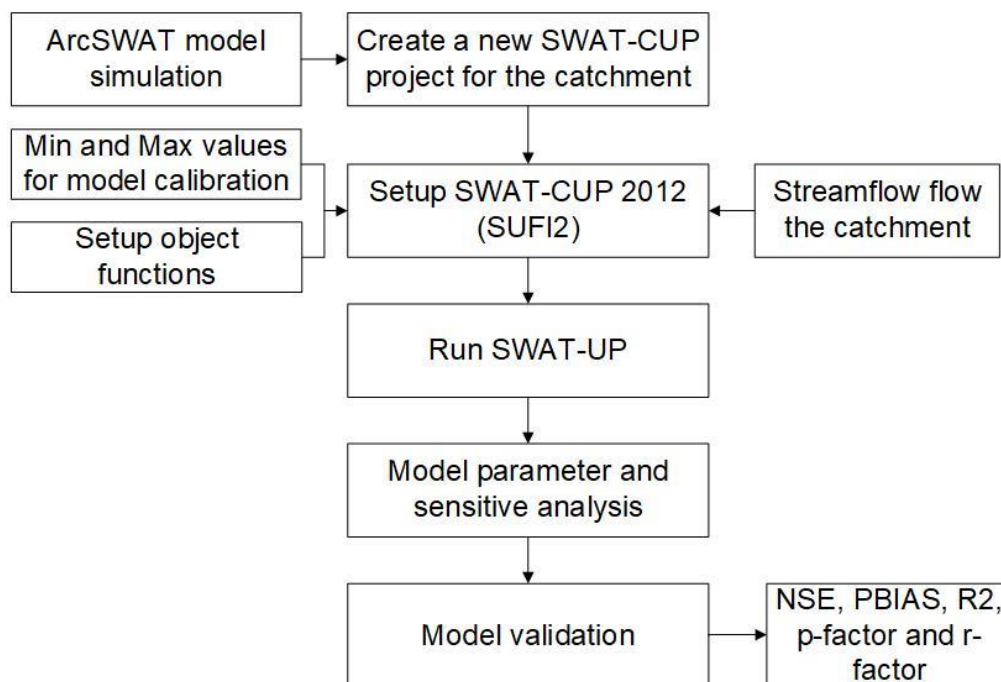


Figure 4.3: Calibration and validation procedure using SWAT-CUP

The SWAT-CUP was established, and a three-year warm-up time was carefully set up to achieve a steady state and mitigate unknown initial conditions for SWAT model, using the objective functions where calibration years were 1993 to 2007 with the prepared streamflow data for the same period. The model calibration was performed

with sensitive parameters according to the values of t-stat and p-value. During model calibration and validation, comparisons of predictions and observations were made, and the model was improved using feedback mechanisms from ongoing assessments. Validation was performed with the same parameters, with the same number of simulations performed during calibration, and newly observed flow data set for the period 2008 to 2018 was used. The statistics and sensitivity analysis were within the range. The sensitive parameters were determined for calibration and validation. A minimum of 300 to a maximum of 1000 simulations were run during each iteration of the simulation.

SUFI-2 uses performance statistics such as the P-factor and R-factor to reduce the large parameter uncertainty it assumes. By bracketing a quantity of measured data that included all uncertainties, the P-factor was utilised to quantify all the uncertainties related to the SWAT model. SWAT model needs to be calibrated and validated for the following reasons (Arnold et al., 2012; Daggupati et al., 2015; Mengistu et al., 2019; Moriasi et al., 2012; Thavhana et al., 2018; Zhang et al., 2009):

- To reduce uncertainty, most of the observed streamflow data was placed in the 95% band using the SUFI-2 algorithm.
- Enhance reliability of model output by calibrating SWAT model observed streamflow data was placed in the 95% band using the SUFI-2 algorithm.
- Some errors in the data preparation, parameterization, and input sources can be used to explain these model uncertainties.
- Errors in human and instrumental data processing could be additional sources of uncertainty. Moreover, uncertainties could potentially originate from the structure of the model.
- Quantify uncertainty and sensitive associated with model predictions and assess the sensitivity of model output to changes in input parameters.

4.6 Statistics for model evaluation

Graphical comparison and numerical criteria are used to rate model performance. The SWAT model predictions are evaluated using studies on these statistical criteria (Mengistu et al., 2019; Moriasi et al., 2007; Yen et al., 2019; Zhang et al., 2009). The evaluation coefficient for deterministic predictions includes Nash-Sutcliffe Efficiency

(NSE), Percent Bias (PBIAS), and Coefficient of Determination (R^2). The proportional quantity of residual discrepancy, also known as "noise", and measured data variance, also known as "information", are equivalently expressed by a normalised statistic called the Nash-Sutcliffe efficiency (NSE). Equation No. 4 is used for the calculation and its represented below.

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

Nash-Sutcliffe efficiency (Nash & Sutcliffe, 1970)

Where Y_i^{obs} is the i^{th} reflection for the constituent being gauged, Y_i^{sim} is the i^{th} simulated value for the component being gauged, Y_i^{mean} is the mean of observed data for the constituent being gauged, and n is the total number of annotations.

The average propensity of the simulated data to be smaller or larger than their observed complements is measured by percent bias (PBIAS). Small values of PBIAS signpost precise model simulation, with 0.0 being the idyllic value. Positive values signify a prejudice in the model's underestimation, whereas negative values signify a bias in the model's overestimation (Gupta et al., 1999). Equation No. 5 is used for calculations and its as follows:

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

Percent bias (Moriasi et al., 1995)

Where Y_i^{obs} is the i^{th} reflection for the constituent being gauged, Y_i^{sim} is the i^{th} simulated value for the component being gauged, Y_i^{mean} is the mean of observed data for the constituent being gauged, and n is the total number of annotations.

The R^2 (Equation No. 6) value is a measure of the strength of the linear correlation between the predicted and observed values. Equation No. 6 is as follows:

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

Coefficient of Determination (Moriasi et al., 1995)

Where Y_i^{obs} is the i^{th} reflection for the constituent being gauged, Y_i^{sim} is the i^{th} simulated value for the component being gauged, Y_i^{mean} is the mean of observed data for the constituent being gauged, and n is the total number of annotations.

4.7 Chapter summary

The chapter was about the methods and materials that were included in this study. Flow diagrams about LULC maps and the SWAT model were presented, as well as the process of creating all the inputs on SWAT model and the calibration and validation using SWAT-CUP. The next chapter is about the results and discussion, addressing the three objectives of the study.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Introduction

This study was aimed at evaluating the impact of LULC changes on the water balance components in C81F quaternary catchment using ArcGIS and the SWAT model in conjunction with remotely sensed data, such as satellite imagery. Consequently, this chapter presents the research results that helped the researcher to realise this primary objective. The research results are presented in three sub-sections that include:

- The LULC changes in the catchment from 1990 to 2018;
- The impact of LULC changes on water balance from 1990 to 2018, and
- The development of mitigation strategies for the limited water resources in the C81F quaternary catchment.

5.2 The LULC changes in the catchment for the period of 1990 and 2018

As stated in the previous chapter, the data used to respond to this sub-question was extracted from the SANLC, as shown in Table 5.1 which indicates that 1990 had 72 classes and 2018 had 73 classes. The difference between the LULC maps (shown in Figures 5.1-5.2) of the same scene at various times is described and quantified by the change detection evaluation.

Table 5.1: Standardised LULC classes for changes between 1990 and 2018.

Class_Name	New Class_Classes	1990	2018
Bare ground	1	40-41	25-31
Build-up	2	42-72	47-67
Cultivated agriculture	3	10-31	32-46, 73
Forest plantation	4	4, 32-34	5-7
Grassland	5	7	12-13
Low shrublands	6	8-9	8-11
Water bodies	7	1-2	14-21
Wetlands	8	3	22-24
Woodlands	9	5-6	0-4

(Source: adapted from the land-cover map reports and legend at <https://egis.environment.gov.za/>, accessed on 20 April 2021).

The nine LULC classes were identified for the catchment and LULC changes were determined, and the LULC were even further reduced from nine to seven classes to suit the SWAT model category, as Table 5.2 stipulates. Low shrublands and grassland were grouped into pasture and woodland together with forest plantation were grouped into mixed forest. SWAT model has specific names that are used to suit the model. The 2000 and 2010 LULC used the seven classes listed in Table 5.2.

Table 5.2: SWAT model LULC reduced to suit the model.

Number	Class Name	SWAT
1	Water	WATR
2	Wetlands mixed	WETL
3	Mixed forest	FRST
4	Pasture	PAST
5	Generic agricultural lands	AGRL
6	Barren land	BARR
7	Urban	URBN

To determine the area of various land cover types and to identify changes that take place within the data range, the classified LULC maps of the four different periods are employed. This assessment is useful in detecting the many alterations that take place in various types of land use, such as urban, and the reduction in forest mix. This study explored the change detection in LULC of the C81F quaternary catchment over the last 28 years. Pasture dominated the LULC in 1990, followed by urban, then mixed forest which accounted for 71.44%, 16.73% and 5.50% of the total area, respectively (Figure 5.1). The least dominant classes were water and barren land. In 2000, the most dominant LULC class was pasture, urban, mixed forest at 70.36%, 16.99% and 6.01% respectively, where least dominated were water, barren land and wetlands with 0.25%, 1.29% and 1.55% respectively.

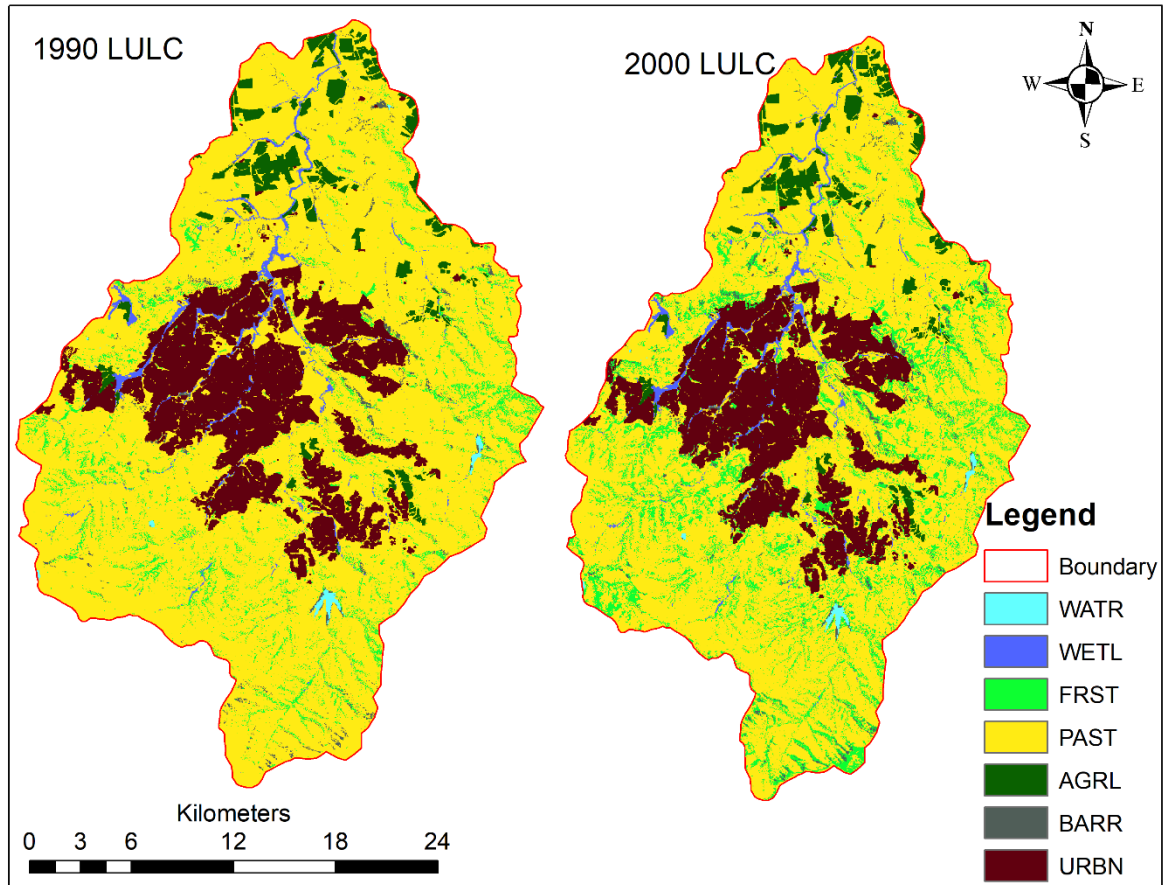


Figure 5.2: The created 1990 and 2000 LULC maps for the C81F quaternary catchment

The 2010 LULC that were dominant are pasture, urban, and mixed forest with 68%, 17.35% and 6.76 respectively, and least dominated were water, wetlands, and barren land with 0,27%, 1.48% and 1.55% respectively. For 2018, the dominant LULC was pasture, followed by urban, then generic agricultural land, compromising 65.08%, 18.82% and 7.96% of the total area, respectively (Figure 5.2).

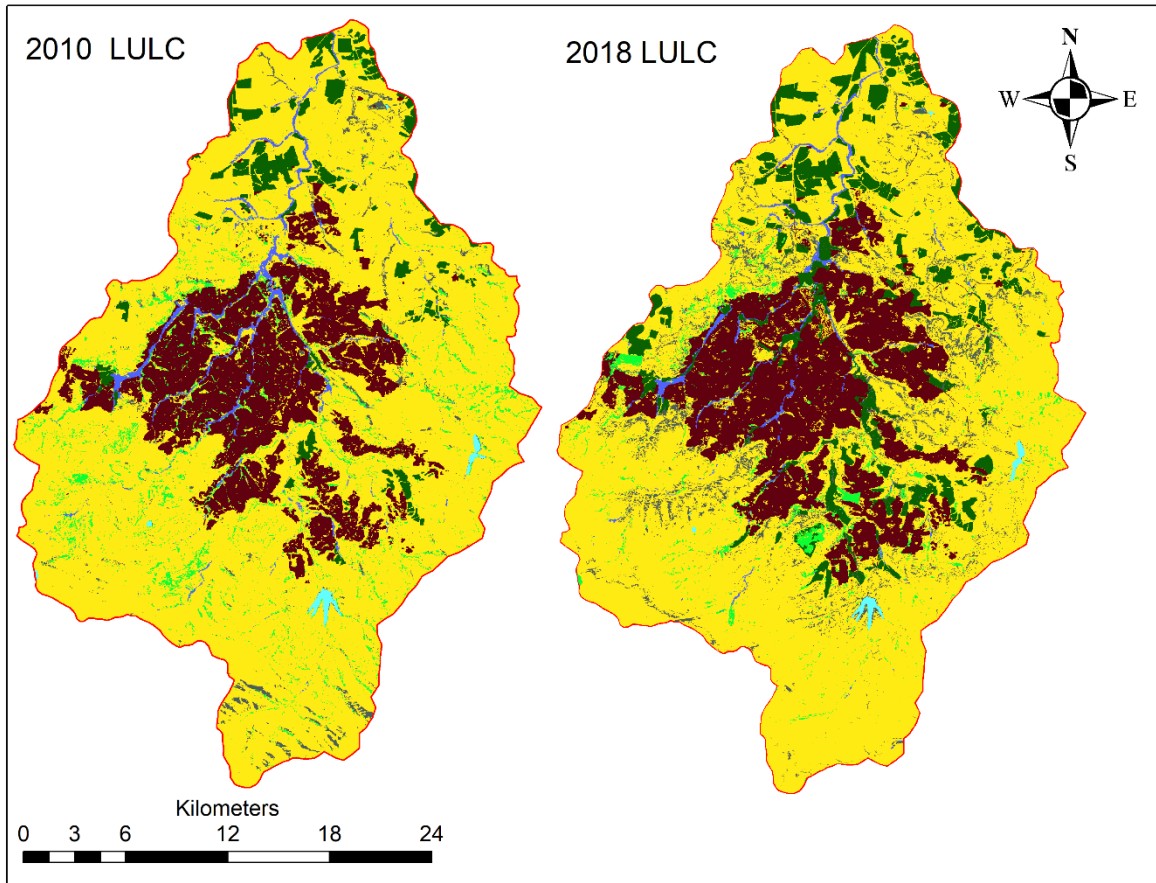


Figure 5.3: The created 2010 and 2018 LULC maps for CF81 quaternary catchment

Table 5.3 shows the LULC classes, coverage area in hectares, percentage, where Table 5.4 shows the magnitude difference in ha and rate of change for a period of 28 years. The LULC classes were reduced into seven classes based on the SWAT model over the years in the catchment area. The post-classification method is used to detect the changes in LULC classes of water, wetlands mixed, mixed forest, pasture, generic agricultural land, barren and urban. Table 5.4 illustrates the change detection in LULC based on categorised data. The negative rate of change indicates a decrease in LULC class.

The study area's relative changes in land usage between 1990 to 2018 have displayed different patterns, such as linear and prominent for other years due to most classes were increasing gradually from 1990 to 2018 and some were decreasing. Such changes have shown negative changes in three classes (mixed forest, wetlands mixed, and pasture). The changes occurred in the study area for the first ten years

(1990 - 2000) shows a decrease in two classes which are pasture and wetlands mixed with a negative rate of change. Pasture and wetlands mixed reduced with 73.08 ha and 4.06 ha per year respectively. Positive rate of change occurred in barren land, urban, and generic agricultural land where these classes increased with 20.3 ha, 17.59 ha and 4.06 ha annually for 10 years respectively. This shows a link between the reduction of pasture and increase barren land.

The LULC in the study area continue to decrease the classes of pasture and wetlands mixed with a negative rate of change of 103.72 ha and 4.52 ha per annum. Mixed forest is the highest positive rate of change of 50.96 ha followed by urban of 24.07 ha and barren land of 17.29 ha. These changes took place for 10 years from 2000 to 2010. The changes in LULC for a period of 2010 to 2018, have positive rate of change for generic agricultural land, barren land, and urban areas with values of 354.30 ha, 260 ha, and 124 ha per year respectively. Mixed forest, pasture and wetlands mixed have negative rate of change which were 391.88 ha, 316 ha and 31.29 ha annually respectively.

Mixed forest compared to pasture shows a decrease of 2280.32 ha with a negative change (61.27%). The second negative change (31.06%) over 28 years is wetlands with a decrease of 338.33 ha. The overall degradation in pasture covered an area between 1990 and 2018, have decreased by 4303.50 ha showing a negative change (8.90%). These were the major LULC classes showing decline. A positive rate of change stipulates an increase in LULC changes. Barren land and generic agricultural land increased respectively with 2456.27 and 3024.62 ha over 28 years (Table 5.4).

Table 5.3: Coverage in area (ha and percentage) LULC classes in the study area

Class Names	SWAT	1990		2000		2010		2018	
		Area (Ha)	Area (%)	Area (Ha)	Area (%)	Area (Ha)	Area (%)	Area (Ha)	Area (%)
Water	WATR	162.4	0.24	169.16	0.25	180.86	0.27	189.46	0.28
Wetlands mixed	WETL	1089.41	1.61	1048.81	1.55	1001.40	1.48	751.08	1.11
Mixed forest	FRST	3721.58	5.50	4066.67	6.01	4576.30	6.76	1441.26	2.13
Pasture	PAST	48339.88	71.44	47609.10	70.36	46571.94	68.83	44036.38	65.08
Generic agricultural land	AGRL	2361.51	3.49	2402.11	3.55	2551.70	3.77	5386.13	7.96
Barren land	BARR	669.88	0.99	872.88	1.29	1045.81	1.55	3126.15	4.62
Urban	URBN	11320.35	16.73	11496.29	16.99	11737.00	17.35	12734.55	18.82

Table 5.4: Change rate of different LULC classes in the study area

Class Names	SWAT	LULC change: 1990-2000			LULC change: 2000-2010			LULC change: 2010-2018			LULC change: 1990-2018		
		Change in ha	Rate of change	Change (%)	Change in ha	Rate of change	Change (%)	Change in ha	Rate of change	Change (%)	Change in ha	Rate of change	Change (%)
Water	WATR	6.76	0.68	4.16	11.70	1.17	6.91	8.60	1.08	4.76	27.06	0,93	16,66
Wetlands mixed	WETL	-40.60	-4.06	-3.73	-47.41	-4.74	-4.52	-250.32	-31.29	-25.00	-338.33	-11,67	-31,06
Mixed forest	FRST	345.09	34.51	9.27	509.63	50.96	12.53	3135.04	391.88	-68.51	2280.32	-78,63	-61,27
Pasture	PAST	-730.78	-73.08	-1.51	1037.16	103.72	-2.18	2535.56	316.95	-5.44	4303.50	148,40	-8,90
Generic agricultural land	AGRL	40.60	4.06	1.72	149.59	14.96	6.23	2834.43	354.30	111.08	3024.62	104,30	128,08
Barren land	BARR	203.00	20.30	30.30	172.94	17.29	19.81	2080.34	260.04	198.92	2456.27	84,70	366,67
Urban	URBN	175.94	17.59	1.55	240.71	24.07	2.09	997.55	124.69	8.50	1414.20	48,77	12,49

Clay loam is the highest soil texture type in the catchment. Owing to its negative surface charge, it has a greater capacity to absorb cations and certain nutrients, which is imperative for the quality and health of the soil (Suliman et al., 2018). Due to its strong impact on the flow of water, air, and nutrients in the soil, the amount of clay loam has a significant impact on the chemical and biological processes of the soil (Bonanomi et al., 2011). It is common knowledge that soil organic carbon is a function of numerous soil physical properties, including aggregation, bulk density, moisture content, total porosity, Zetterberg limits, and dispersion clay (Davari et al., 2020). Notably, clay loam is a great soil property texture which is very good for cultivated agriculture which is shown as evident about the catchment because it has the highest increase in cultivated agriculture (Suliman et al., 2018). In short, the catchment's soil is suitable for agriculture. Clay loam has the highest soil class with a coverage of 76.71% (Table 5.5).

Table 5.5: Soil coverage and properties

SWAT Class	Properties	ha	%
Ws13-2ab-985	Loam	15677.98	23.17
Fr20-3bc-575	Clay	81.20	0.12
I-Bc-L-2-640	Clay-loam	51905.82	76.71

5.2.1 Discussion

This section determined the LULC adjustments in the catchment for the period of 1990 to 2018. Based on the LULC change analysis, it can therefore be confirmed that the water surface area has increased by 16.66% from 1990 to 2018. There are two known dams in the Thabo Mofutsanyane District Municipality, namely: Metsimatsho and Fika-Patso. The waterbodies include natural (seasonal) and artificial. The amount of water in rivers, estuaries, dams, and lakes, among other bodies of water, is directly impacted by climate variability through precipitation, evaporation, and surface runoff. The distribution and alteration of water resources in a space may have an impact on both human lifestyle and natural biological systems. Changes in the water resource systems may also have an impact on the local vegetation and amplify the effects of climate variability (Trenberth, 2011). Taking everything into account, water-related investments can be made in a variety of ways to boost availability, quality, and efficiency of usage (Prins et al., 2022). As the world's population grows, more water will be needed for domestic and industrial uses, which

will force many water-scarce regions to either import more food or produce more food with less water (Botai et al., 2016).

There was an increase in generic agricultural land from 3.49% to 7.96% in the period under review, the change was more predominant pattern due to the need to develop the agricultural sector. The increase may be attributed to the expansion of the agricultural sector to boost productivity for food security in the catchment and the country. The generic agricultural land includes commercial annual crops pivot irrigated and non-pivoted, commercial annual crops rain-fed/ dryland, cultivated subsistence / small scale annual crops in the study area. Cherry crops and sunflower seed are some of the farming activities in the study area. In South Africa, irrigated agriculture consumes the most water, and this reliance on water creates the risk for all agricultural activities. The increase in generic agricultural land is driven by population growth which is evident by urban increase in the study area, dietary changes were by new crops might be needed for the area, increase demand for agricultural products as Thabo Mofutsanyana district municipality produces 90% of the country's cherry crops and has a huge farming for sunflower seeds. Mixed forest decrease is linked with deforestation where forests are cleared for agricultural purposes which contributes to habitat loss, carbon emission and biodiversity decline. Therefore, the increase in generic agricultural land is due to the demand for food and other agricultural products.

Barren land increased from 0.99% to 4.62% area in the period under review. The slight increase can be attributed to the decrease in mixed forest, from 1990 to 2018 the area in ha decrease from 3721.58 to 1441.26. This shows a drastic decrease in mixed forest. This decrease in mixed forest is linked to the increase in generic agricultural land and increase in barren land. The mixed forest includes contiguous (indigenous), dense forest, woodlands, temporary unplanted plantation forest, open & sparse plantation forest and contiguous low forest & thicket in the study area. Unsustainable land management practices such as deforestation, overgrazing and improper agricultural practices can lead to soil degradation results in barren land increase. Deforestation is the removal of trees has been taking place in the catchment, this is due to the increase in barren land.

Plantations for agriculture and forestry are significant economic endeavours that provide regional employment and societal advancement (Chemura et al., 2020).

However, the fundamental impact of plantations and other woods on water resources is that they transpire more water than crops, pastures, and other similar land covers (Prosser & Walker, 2009). This is to support the decrease in forest mix and pasture. Plantations have high rates of ET due to the presence of vegetation which shows the decrease in ET in 2018 modelling. The surface runoff modelled using SWAT shows an increase in this study area from 1990 to 2018 and a decrease in ET. Plantation trees consume more water per unit area per year than agricultural land uses like cereals, pastures, and other crops, which lowers runoff and discharge in areas where they are prevalent (Chemura et al., 2020). The pasture in the study area includes grassland and woodlots (young, mature, and clear felled). The decrease in plantation results in implications for ecosystem health and resilience therefore a linear pattern occurred in this LULC class.

The benefits of forests and trees for people and the environment include supporting livelihoods, supplying clean air and water, preserving biodiversity, and combating climate change. Due to its role in regulating critical ecological processes including water availability, nutrient intake and decomposition, soil is an essential component of the woodland and forest ecosystems. Foresters have historically evaluated the potential of locations to produce healthy forests using their understanding of the chemical and physical qualities of soil (Shao et al., 2020). These changes result in population increase, severity of drought and floods, water scarcity for irrigation and drinking, reduced runoff, and increased evaporation. Catchment management is especially critical for climate change adaptation in a water-stressed country like South Africa. Through evidence-based water licensing, predicting changes in land cover may help create resilience to climate change (Mbileni, 2015). Mixed forest acts as natural reservoirs by storing water in soils, vegetation, and organic matter, where the water is then released through transpiration and evaporation gradually. Therefore, the loss of mixed forest the storage capacity is diminished, leading more rapid runoff and reduced water availability during dry seasons which results in a linear decrease pattern.

The increase in urban area from 1990 to 2018 was from 11320.35 ha to 12734.55 ha, this shows the link between the decrease in pasture and mixed forest together with the increase in urban area due to converting the natural vegetation will reduce the landscape to intercept rainfall, promote infiltration and regulate surface runoff.

Urban area increased with 48.77 ha annually for 28 years. The LULC change brought on by deforestation, urbanisation, and cultivation using different tillage techniques altered the surface runoff, which ultimately led to a change in the frequency of food production (Kumar et al., 2022). The urban area includes commercial, industrial, urban townships, urban rural, urban. Hospitals, schools, homes, firms, office buildings and shopping malls are found in the study area. Four LULC maps were produces and most changes happened between 2010 to 2018 and 1990 to 2018, when these two periods are comparing most changes happened in the period 1990 to 2018.

5.3 Model calibration and validation.

The SWAT model was calibrated and validated to improve performance by comparing the observed values with the simulated streamflow and modifying a few parameters. The monthly streamflow observation data is from flow gauging station C8H028 used for calibration and validation. In order to ensure that the climate data used for calibration and validation are not significantly different that is, that wet, moderate, and dry years occur in both periods data are most commonly split by time periods (Arnold et al., 2012). A little over two-thirds of the monthly streamflow (data points) from this station's observations between 1993 to 2007 were used for calibration, while the outstanding one-third from 2008 to 2018 was used for model validation(Abbaspour, 2015). A minimum of 300 to a maximum of 1000 simulations were run during each iteration of the simulation. The nine sensitive parameter were used for calibration and validation due to being sensitive on streamflow output based on the low p-values and large t-stat values and other studies (Mengistu et al., 2019; Scott-Shaw et al., 2022; Thavhana et al., 2018).

Table 5.6 shows all the sensitive parameters together with their description, all these parameters were chosen for the study area due to sensitive analysis. In SWAT, a model calibration and validation of streamflow requires ET, lateral flow, surface runoff which these were determined during the modelling stage. The LULC map for 2018 was used due to most changes happening in this year from the period of the study and the fact that it's the most recent year.

Table 5.6: Sensitive parameters used for model calibration and validation.

No.	Parameter name	Description	Function
1	CN.mgt	SCS runoff curve number	Surface runoff
2	ALPHA_BF.gw	Baseflow alpha factor (days)	Baseflow
3	GW_DELAY.gw	Groundwater delay (days)	Baseflow
4	GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	Baseflow
5	SLSUBBSN.hru	Average slope length	Topography
6	ESCO.hru	Soil evaporation compensation factor	Surface runoff
7	SOL_AWC(..).sol	Available water capacity of the soil layer	Surface runoff
8	SOL_K(..).sol	Saturated hydraulic conductivity	Surface runoff
9	CH_N2.rte	Manning's "n" value for the main channel	Surface runoff

A global sensitivity analysis is indicated in Table 5.7 by showing the sensitive parameters in the catchment. P-values and t-statistic values were used to evaluate the SUFI2 parameters' sensitivity, as shown in Table 5.7. The more sensitive parameters are those with larger absolute t-stat values, and the significance of the sensitivity is determined by the P-value. The parameters are categorised as having sensitive significance when the P-value is near 0.

Table 5.7: Sensitive parameters in the study area

Parameter Name	Description	t-Stat	P-Value
R_CN2.mgt	SCS runoff curve number	-1.613	0.1378
V_ALPHA_BF.gw	Baseflow alpha factor (days)	0.5927	0.5665
V_GW_DELAY.gw	Groundwater delay (days)	0.754	0.4683
V_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.136	0.8946
R_SLSUBBSN.hru	Average slope length	-0.3418	0.7396
R_ESCO.hru	Soil evaporation compensation factor	1.145	0.8876
R_SOL_AWC(..).sol	Available water capacity of the soil layer	-1.243	0.2422
R_SOL_K(..).sol	Saturated hydraulic conductivity	0.566	0.5838
R_CH_N2.rte	Manning's "n" value for the main channel	0.8529	0.4137

The model parameter performance indices were calculated using monthly time step data. The calibration results in Figure 5.3 showed that the observed and simulated

flows between 1993 and 2007 were consistent and reasonably close to each other. Although the validated results in Figure 5.4 showed consistency in the stream flow simulation between 2008 and 2018, the observed and simulated peak flow showed some highs and lows which is good for validation.

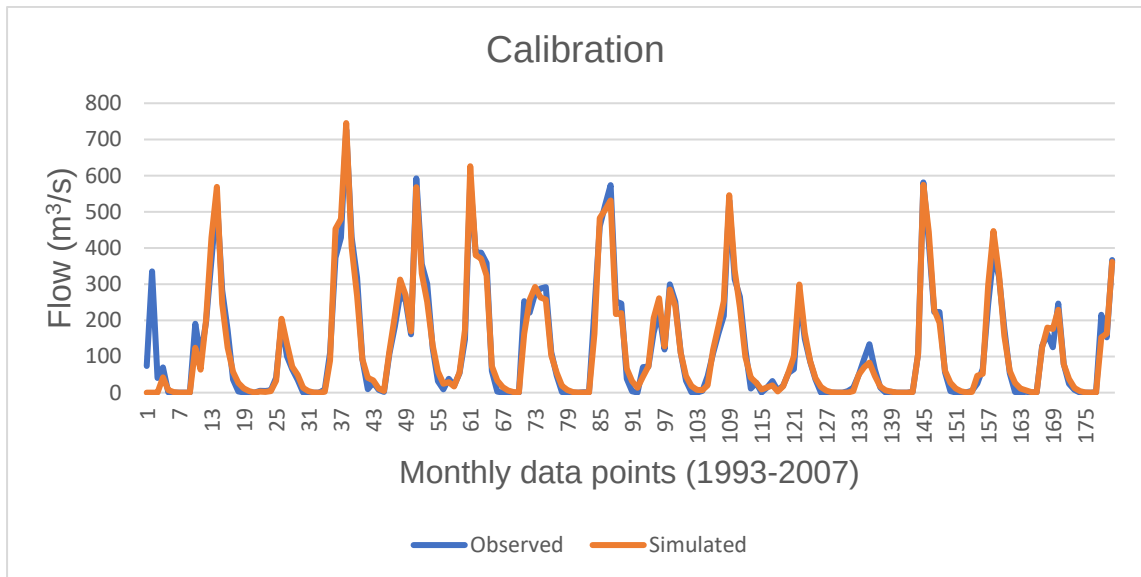


Figure 5.3: Observed and simulated calibration for the period 1993 to 2007.

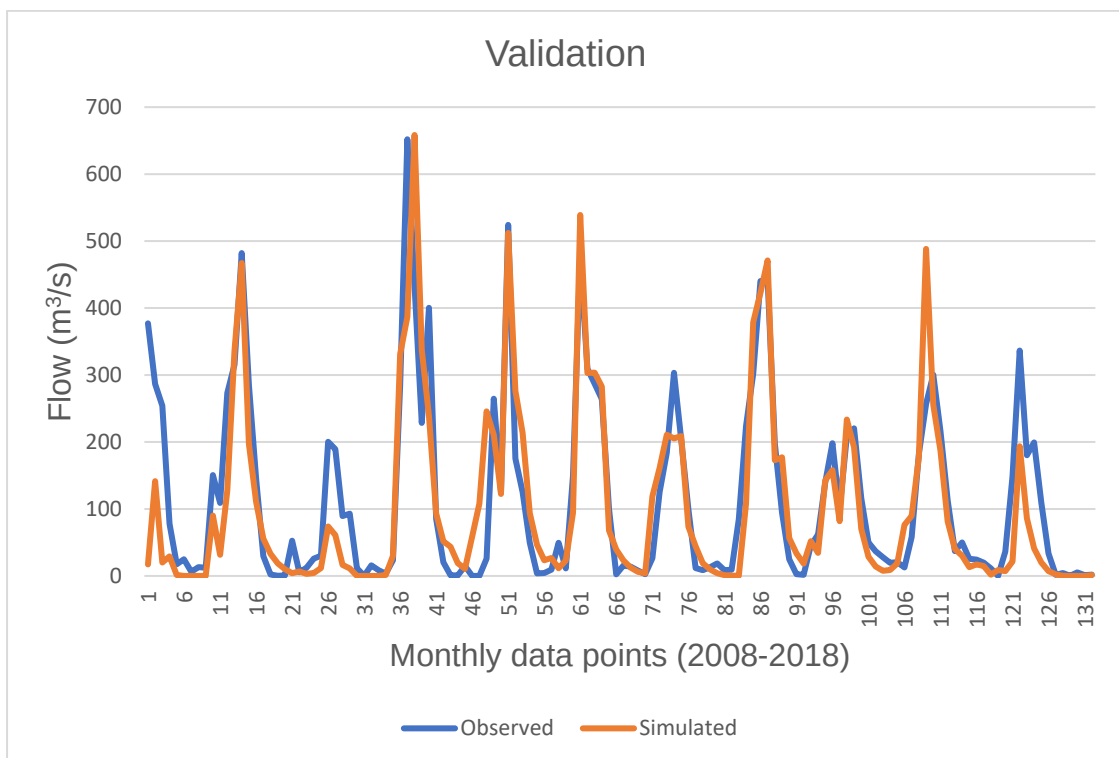


Figure 5.4: Observed and simulated for model validation for the period 2008 to 2018.

Two key categories of statistical evaluations, namely: model performance evaluation and model prediction uncertainty, were used to evaluate the performance of the best parameter sets chosen in the sensitivity analysis (Table 5.8). The prediction uncertainty in SUFI2 (one of the programs in SWAT-CUP) is expressed by the 95PPU (95 percent prediction uncertainty), which is displayed as the green region in Figures 5.5 and 5.6 for the calibration and validation processes, respectively. Every parameter has a minimum and a maximum value, for calibration to run smoothly outlined by (Guug et al., 2020). All the minimum and maximum values of the parameters in the study area are within the range, which is satisfactory. The method for each parameter was selected based on the sensitivity of the results. Table 5.8 shows the fitted parameter values.

Table 5.8: Methods of a parameter change, initial adjustment intervals, and calibrated values for each parameter

No.	Parameter name	Method of change	Fitted Value	Min Value	Max value
1	CN.mgt	Relative	0.007869	-0.050747	0.066485
2	ALPHA_BF.gw	Replace	0.720652	0.584164	0.857140
3	GW_DELAY.gw	Replace	49.470795	-1.731816	100.673400
4	GWQMN.gw	Replace	-0.036602	-0.490937	0.417733
5	SLSUBBSN.hru	Relative	6.552101	2.673359	10.430843
6	ESCO.hru	Relative	0.162009	-0.118700	0.442727
7	SOL_AWC(..).sol	Relative	0.803998	0.570457	1.037539
8	SOL_K(..).sol	Relative	1.867181	1.658497	2.075865
9	CH_N2.rte	Relative	0.434512	0.350987	0.518037

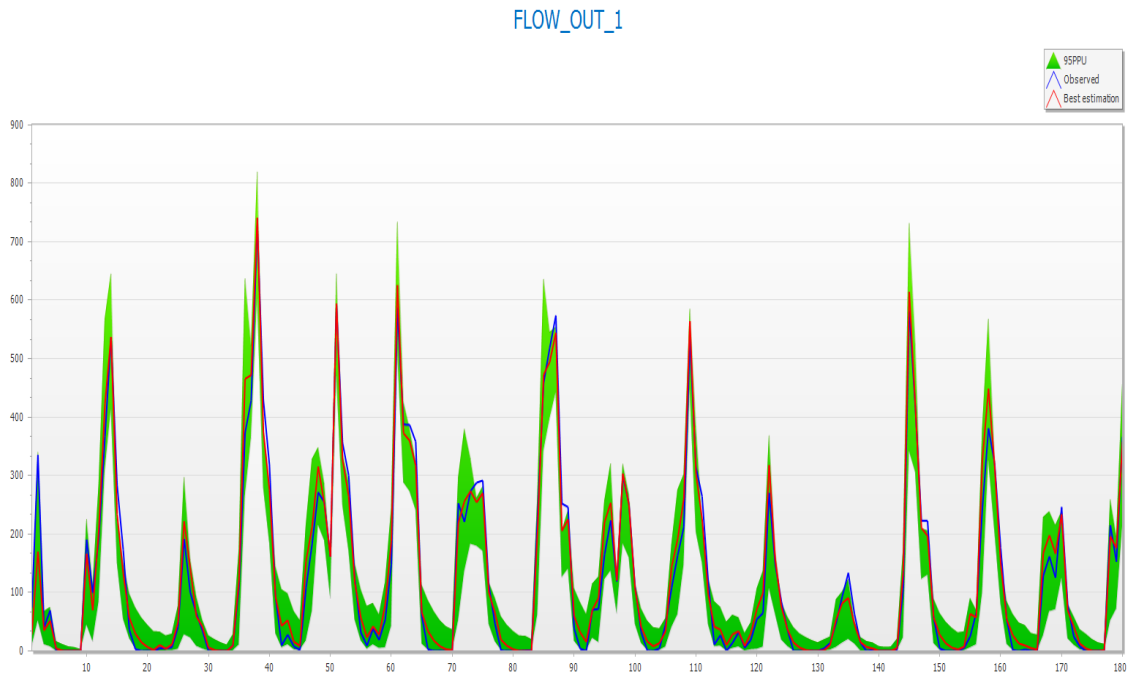


Figure 5.5: 95PPU plot from SWAT-CUP calibration

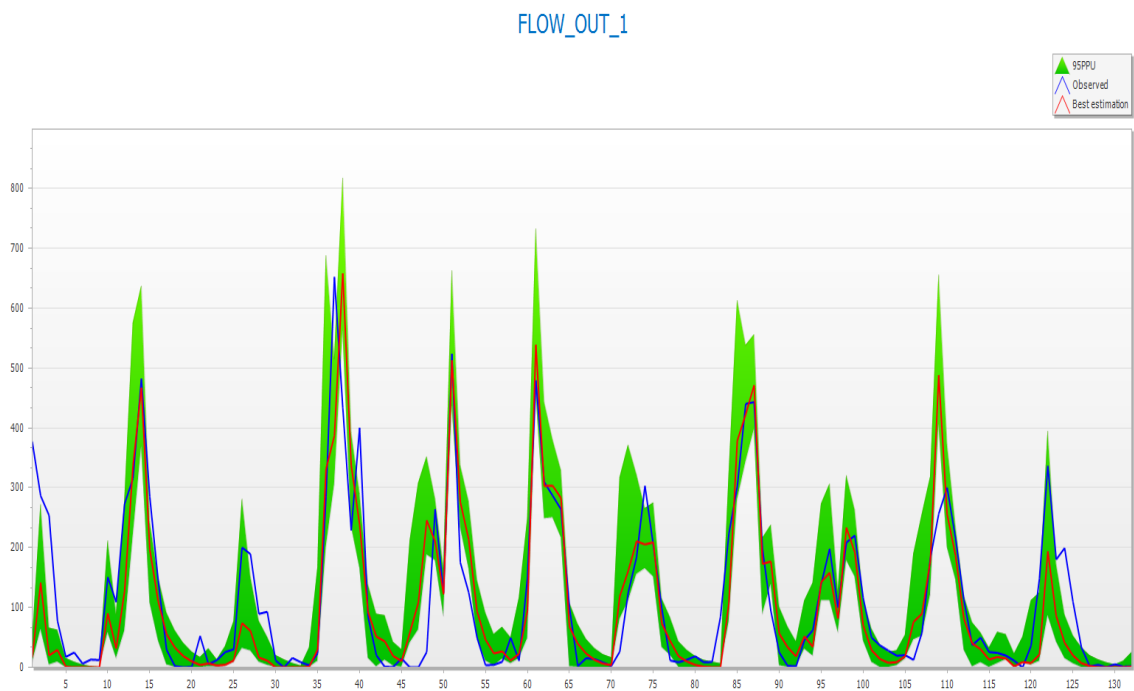


Figure 5.6: 95PPU plot from SWAT-CUP calibration

Figures 5.7 and 5.8 show the results of the coefficient of determination (R^2) after calibration and validation, which was discovered to be 0.79 and 0.72, respectively. Since it is greater than 0.6, this indicates that the results are good.

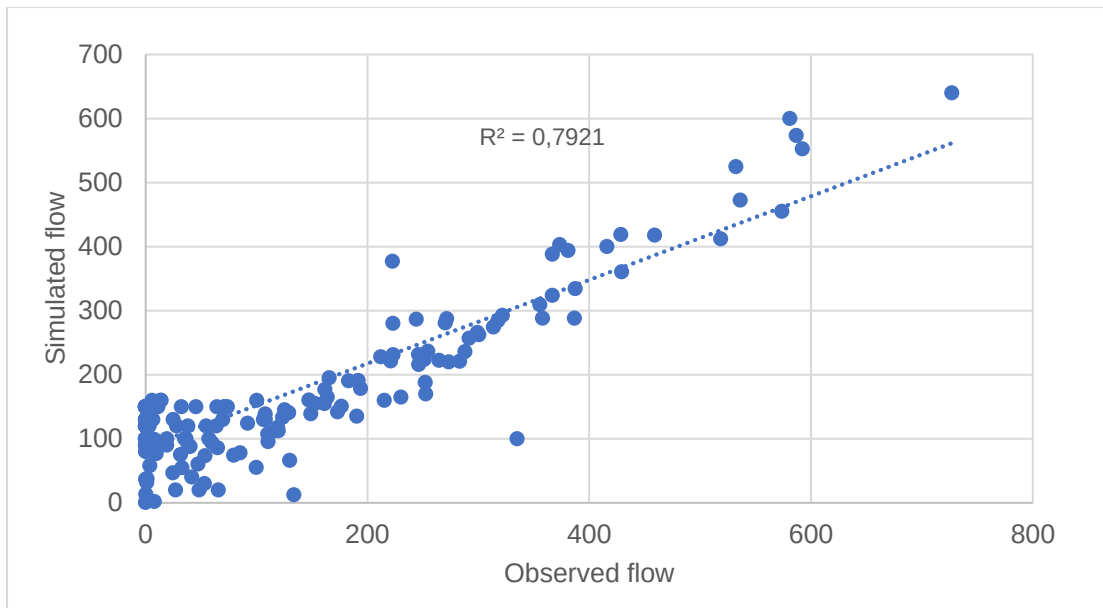


Figure 5.7: Coefficient of Determination (R^2) for calibration

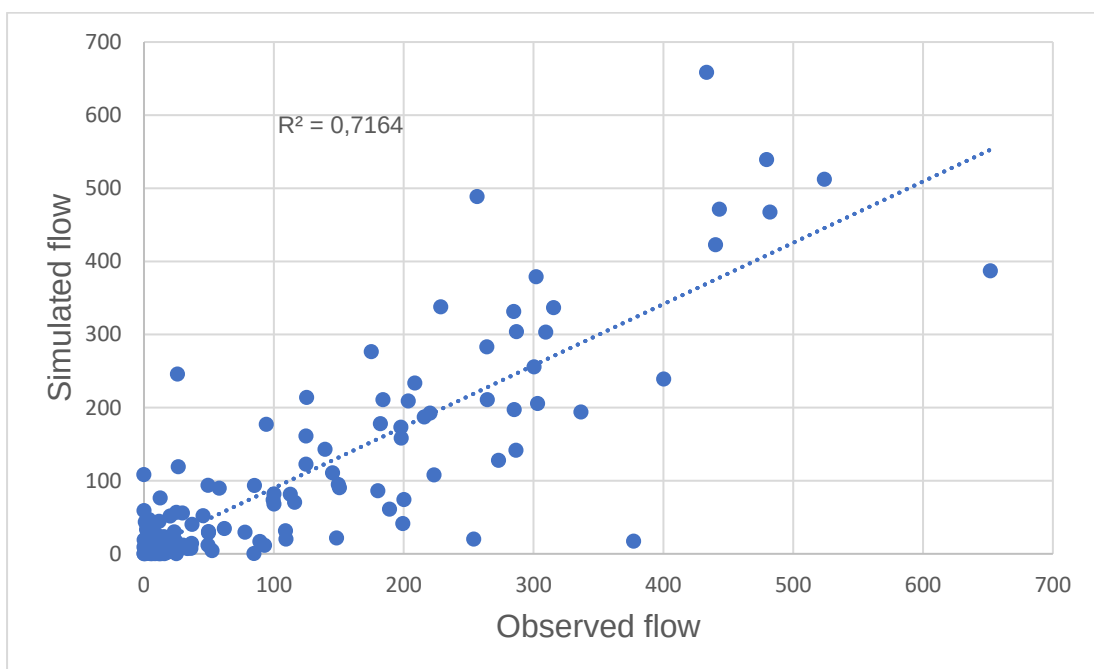


Figure 5.8: Coefficient of Determination (R^2) for validation

The R-factor and P-factor, two indices used to measure model uncertainty, were computed. The 95PPU was well bracketed during the calibration period from 1993 to 2007, with a P-factor and an R-factor of 0.76 and 0.60, respectively, while during the validation period from 2008 to 2018, the values changed to 0.60 and 0.64, respectively. This is demonstrated in Table 5.9. The level of uncertainties in input variables, such as rainfall, is indicated by the slight decrease in P-factor during

validation from 0.76 to 0.63. The sensitive parameters produced results in Table 5.9 where the statistics were satisfactory.

Table 5.9: Summary of statistics for calibration (1993-2007) and validation (2008-2018) processes with flow data in the outlet of the donor catchment

Process	P-factor	R-factor	R ²	NSE	PBIAS
Calibration	0.76	0.60	0.79	0.72	-3.6
Validation	0.63	0.64	0.72	0.69	10

5.3.1 Discussion

Sensitivity analysis refers to the estimation of how quickly the output of a model will change in response to changes in the model's parameters (inputs). Identification of important parameters and parameter precision needed for calibration is a necessary process. After a few trials and errors, Table 5.8 illustrates the sensitive parameters selected for the study area. Data that encompassed typical, rainy, and dry years were used for calibration and validation. When the SWAT2012 modelling in the C81F quaternary catchment was done using the model performance ratings, graphic results during calibration (Figure 5.5) and validation (Figure 5.6) indicated satisfactory calibration and validation over the range of streamflow, even though calibration displayed better results than the validation results. To assess the simulation's performance, quantitative statistics and criteria from Moriasi et al. (2007) were applied. The calibration and validation NSE values for the monthly streamflow were 0.70 and 0.69, respectively. The NSE ratings for calibration and validation were extremely good and good, respectively, according to Moriasi et al. (2007). The NSE measures how well the 1:1 line fits the observed versus simulated data plot.

The coefficient of Determination (R^2) needs to be greater than 0.5 where calibration was very good with 0.79 (Figure 5.7) and validation with 0.72 (Figure 5.8), which was still very good. These values of R^2 indicate a lower error variance because they are greater than 0.7. The p-factor value must be greater than 0.7 and calibration was very good with 0.76, whereas validation results were not pleasing with 0.63. R-factor resulted in 0.60 and 0.64 for calibration and validation, respectively. The calibration and validation's strength and effectiveness are shown by the P-factor and R-factor indices. There must be a balance between the two because a higher P-factor value can be obtained at the expense of a higher R-factor value. The parameter ranges are

regarded as calibrated parameters once acceptable R-factor and P-factor values have been attained through iteration.

For both calibration and validation, the average magnitude of the monthly streamflow values that were simulated fell within a very good range ($PBIAS_{10} < \pm 10$) (Table 5.9). Calibration PBIAS was -3.6, where the negative value denoted a bias in the model's overestimation. Validation was 10, where the positive value denoted a bias in the model's underestimation. These statistical results display satisfactory findings for both calibration and validation. The sensitive analysis looks at the t-stat and p-value for calibration. Table 5.9 shows the results, where higher absolute t-stat values are more sensitive, while the P-value regulates the significance of the sensitivity.

5.4 Precipitation Analysis

Precipitation is one of the inputs on SWAT model and it has a huge impact on how the model behaves. The study area consists of four weather stations namely: witsieshoek, Harrismith, Kestell, and Van reenen. Figure 5.9 shows the measured precipitation data from both SAWS and ARC respectively. The gaps for witsiehoek happened from January 1990 to May 2000 and some gaps were incurred between 2011 to March 2015, this shows that data was missing. Harrismith experienced missing data from January 1990 to December 1994, and some gaps in between 1997, 2000, 2004, January to December 2005, 2006. Kestell had all the data for the whole 28 years, and Van reenen experienced missing data from January 1990 to July 1993. Mechanical stations were used in this station for the data before the year 2000 and automatic stations used after 2000 (Moeletsi et al., 2022). The necessity for WGEN is to address this issue by producing data with similar statistical attributes as the measured data was because measured weather data are frequently insufficient in terms of length, completeness, and spatial coverage (Senent-Aparicio et al., 2021). Figure 5.10 shows precipitation generated by WGEN to fill the missing data.

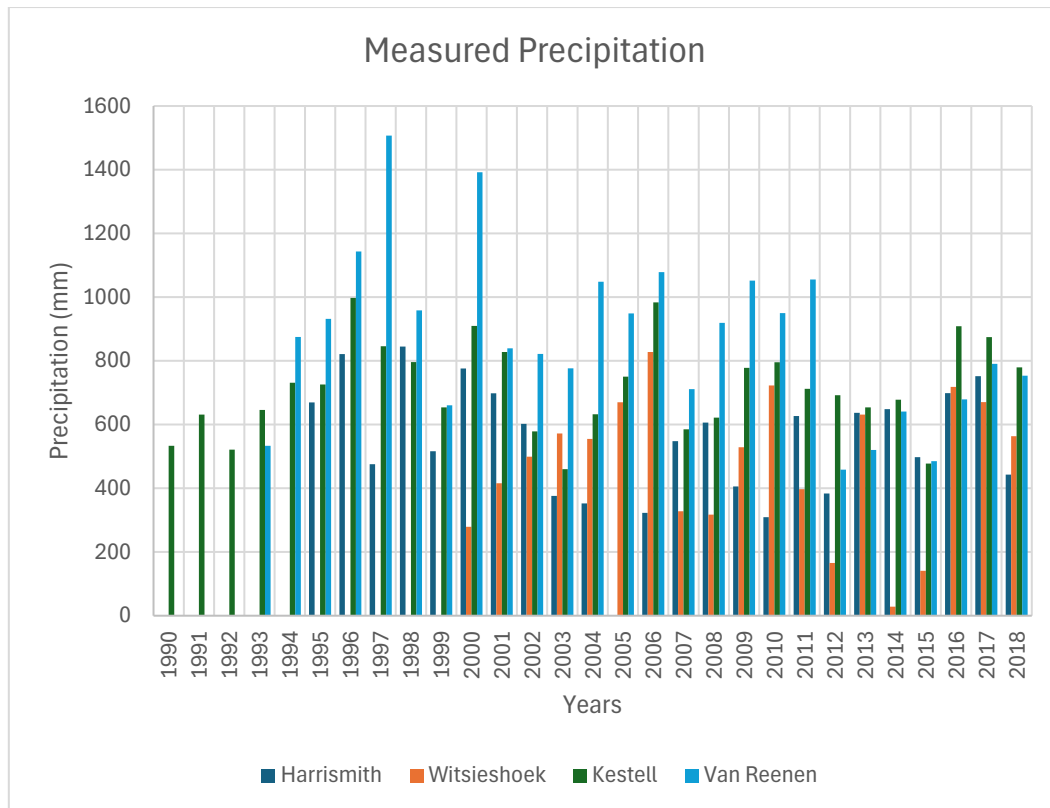


Figure 5.9: Measure data from precipitation stations.

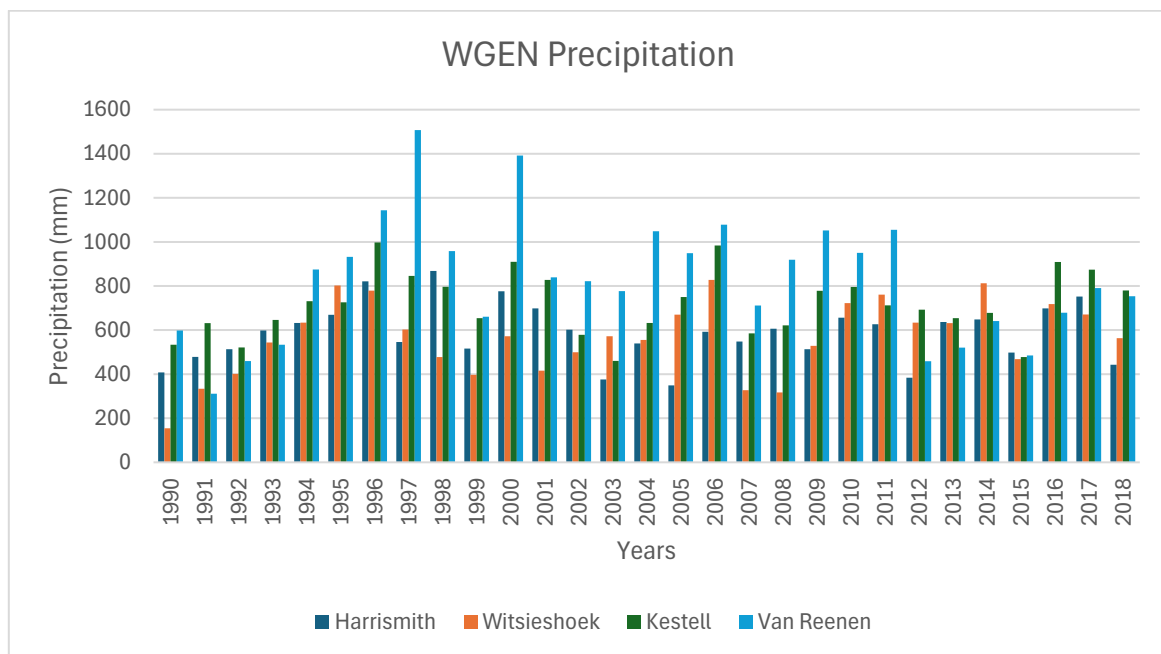


Figure 5.10: Measured data from precipitation stations with corrected (gaps) data from WGEN.

5.4.1 Discussion

The study area experienced long growing season between October to March, in this period high precipitation is experienced. The annual precipitation for the study area ranges from 311,4mm to 1507 mm. Witieshoek experienced the high annual precipitation in 2006, 2014, 1995, of magnitude 827.8 mm, 812.37 mm, and 802.3 mm respectively. Therefore, high precipitation can result in flooding which causes infrastructural damage, soil erosion and crop damage. Precipitation variation was recorded from 1990 with 154.2 mm and 572.1 mm in 2000, 722.63 mm in 2010 and 563.57 mm in 2018. Therefore, witieshoek station shows the change in precipitation starting with the lowest annual value and ending with the value below the one recorded for 2010, most decreased happened to October to December experiencing less rainfall compared to the year 2010. The variation in precipitation affects the water availability in rivers, reservoirs where shortage in water can be a result of below average which promotes increased competition for limited water as a resource and conflicts over water allocation between different uses such as agriculture, industry, and municipalities. Low rainfall in certain years results in wetlands, rivers and lakes experiencing reduced water levels, impacting aquatic species and ecosystem services such as water purification.

Harrismith station experienced annual precipitation of 407.6 mm in 1990, 775.8 mm in 2000, 655.96 mm in 2010 and 442,72 mm in 2018. The lowest rainfall recorded on this station is 348.98 mm (2005). The high annual precipitation occurred in 1998, 1996 and 2000 with 868 mm, 821 mm, and 775.8 mm respectively. This shows a decrease in precipitation from 1990 to 2018 with high recorded values in the middle of the 28 years. Kestell station experienced the high annual precipitation in 1996, 2006, 2000 of 997.8 mm, 983.7mm, and 909.6 mm. The study area shows an increase in urban, high precipitation affects urban flooding, property damage and disruption to transportation networks where low precipitation will lead to water restrictions, water supply disruptions and increased demand on water treatment and purification. The lowest recorded annual precipitation happened in 460 mm in 2003. The variation in precipitation shows that there were most years experienced precipitation lower than MAP of 690 mm and the highest annual precipitation was experienced in 1997 and 2000 by the van reenens station.

Precipitation variation affects agricultural productivity directly, below average precipitation can lead to drought conditions, then farmers will struggle with water scarcity for irrigation. The health and functioning of terrestrial and aquatic ecosystems are affected by habitat degradation, reduced biodiversity, increased stress on plant and animal due to low precipitation. Precipitation variations affects the water balance components such as surface runoff, lateral flow, percolation, and evapotranspiration. Surface runoff is directly influenced, high precipitation leads to higher streamflow as more water enters rivers, stream, and dams, where low precipitation results in reduced streamflow, potentially leading to low-flow conditions, water scarcity, impacts on aquatic ecosystems and water dependent industries such as agriculture and municipal water supply. The volume and velocity of the lateral flow is affected by precipitation variations, where higher lateral flow leads to soil erosion, sedimentation in water bodies, flooding particularly in areas with steep slopes, poorly vegetated. Low precipitation results in reduced percolation leading in meeting water demand for agriculture, industry, and domestic purposes. ET is influenced by higher precipitation where there will be increased soil moisture availability and plant transpiration. The variation in precipitation has an impact on the water balance components, more studies will be done where in depth analysis of all the climate components will be done.

5.5 The impact of LULC changes on water balance for the period of 1990 to 2018

This section details the effects of LULC modifications on the water balance from 1990 to 2018. The catchment's hydrology was modelled by means of the ArcSWAT model, using the following input data: the LULC map of 1990 as a baseline scenario, reclassified to fit the naming and syntax. The other input data on the model were weather data, DEM, and a soil map which were all utilised to delineate sub-basins and HRUs. Furthermore, a portion of the sub-basin report is shown in Figure 5.11, which provides an in-depth description of the distribution of the soil, land, and slope classes after applying thresholds for the catchment and all sub-basins. The research area's total drainage area is 67665.24 hectares. The catchment was subdivided into 25 sub-basins and 90 HRU's for 1990 (Figure 5.12) and 92 HRUs for 2018 (Figure 5.13). The hydrologic response units were defined by integrating land use, soil, and

slope classes. To reduce the number of HRUs, threshold percentages of 25% for land use/cover, 10% for slope, and 10% for soil were assigned.

The ArcGIS interface was used to set up and parameterise the model (Arnold et al., 2012). The C81F quaternary catchment, which has an extent of 67665.24 ha, was delineated using a DEM with a 30 m resolution. The SWAT model was used with input data such as soil, DEM, and land use to create 25 sub-basins and 92 HRUs. The SWAT model made simulations from 1990 to 2018. The initialising or warming up of the model takes place over the first three years of runs.

		Area [ha]	Area[acres]	
Watershed		67654.2600	167177.0592	
Number of Subbasins: 25				
		Area [ha]	Area[acres]	%Wat.Area
LANDUSE:				
	Water --> WATR	163.8010	404.7605	0.24
	Wetlands-Mixed --> WETL	1101.4644	2721.7735	1.63
	Mixed forest --> FRST	3267.1367	8073.2583	4.83
	Pasture --> PAST	48685.8852	120305.2566	71.96
	Agricultural Land-Generic --> AGR1	2355.1268	5819.6361	3.48
	Barren land --> BARR	701.0720	1732.3839	1.04
	Urban --> URB1	11379.7740	28119.9904	16.82
SOILS:				
	Fr20-3bc-575	83.2149	205.6282	0.12
	I-Bc-L-2--640	51897.5453	128241.4294	76.71
	Ws13-2ab-985	15673.4998	38730.0016	23.17
SLOPE:				
	0-20	39479.7606	97556.4625	58.36
	20-40	16985.3582	41971.6695	25.11
	40-60	7097.2885	17537.7547	10.49
	60-80	2642.2998	6529.2549	3.91
	80-9999	1449.5528	3581.9176	2.14

Figure 5.11: HRU distribution in the study area

Three soil forms were recognised in the study catchment, and it was also significantly altered so that it would be compatible with SWAT's plant databases by reclassifying them into three classes by using SWAT modelling categories. Sub-basin 1 is where the outlet is located, the reference is from catchment delineation (Figure 5.14), which is at the lowest point of the catchment.

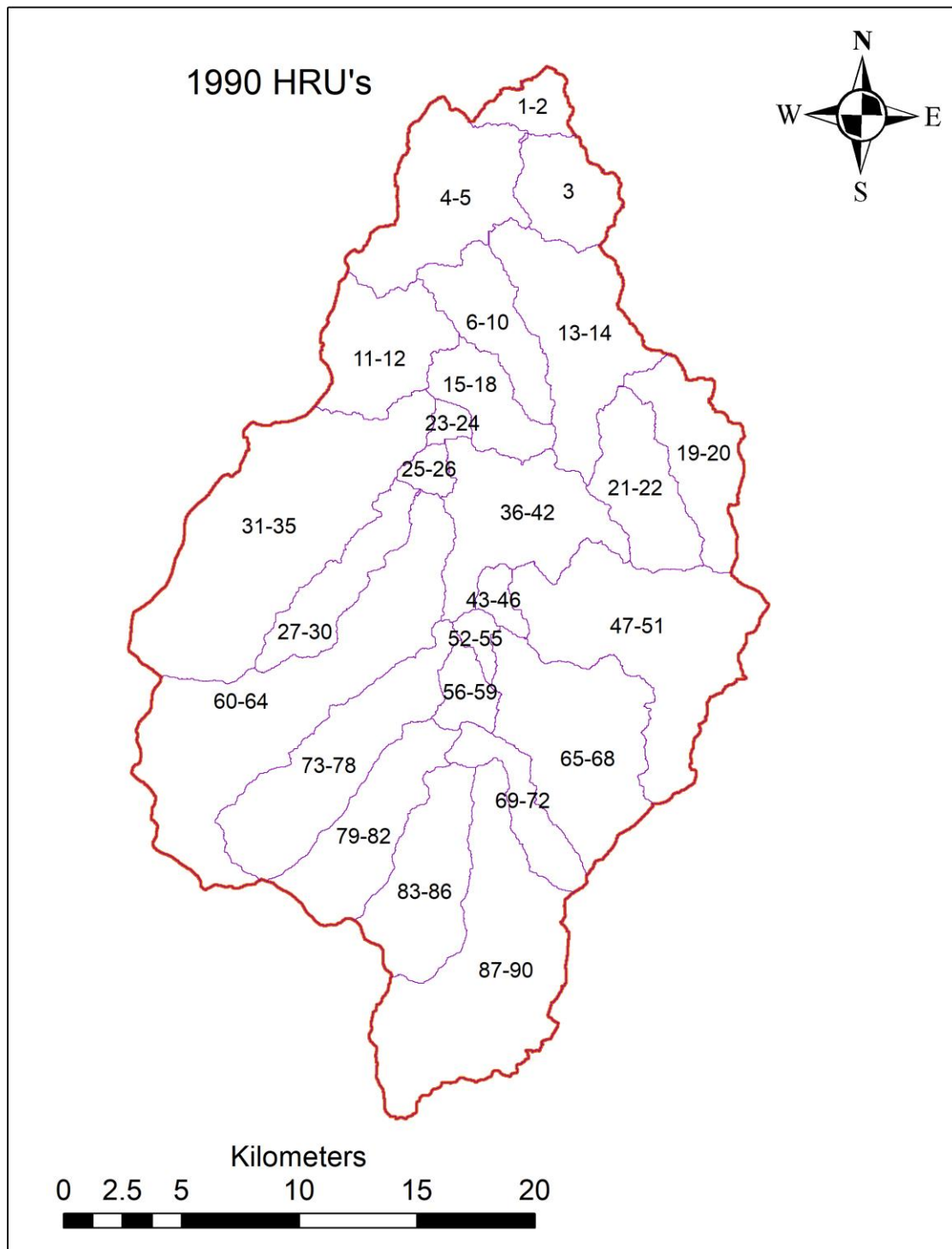


Figure 5.12: HRU's within a catchment using 1990 LULC

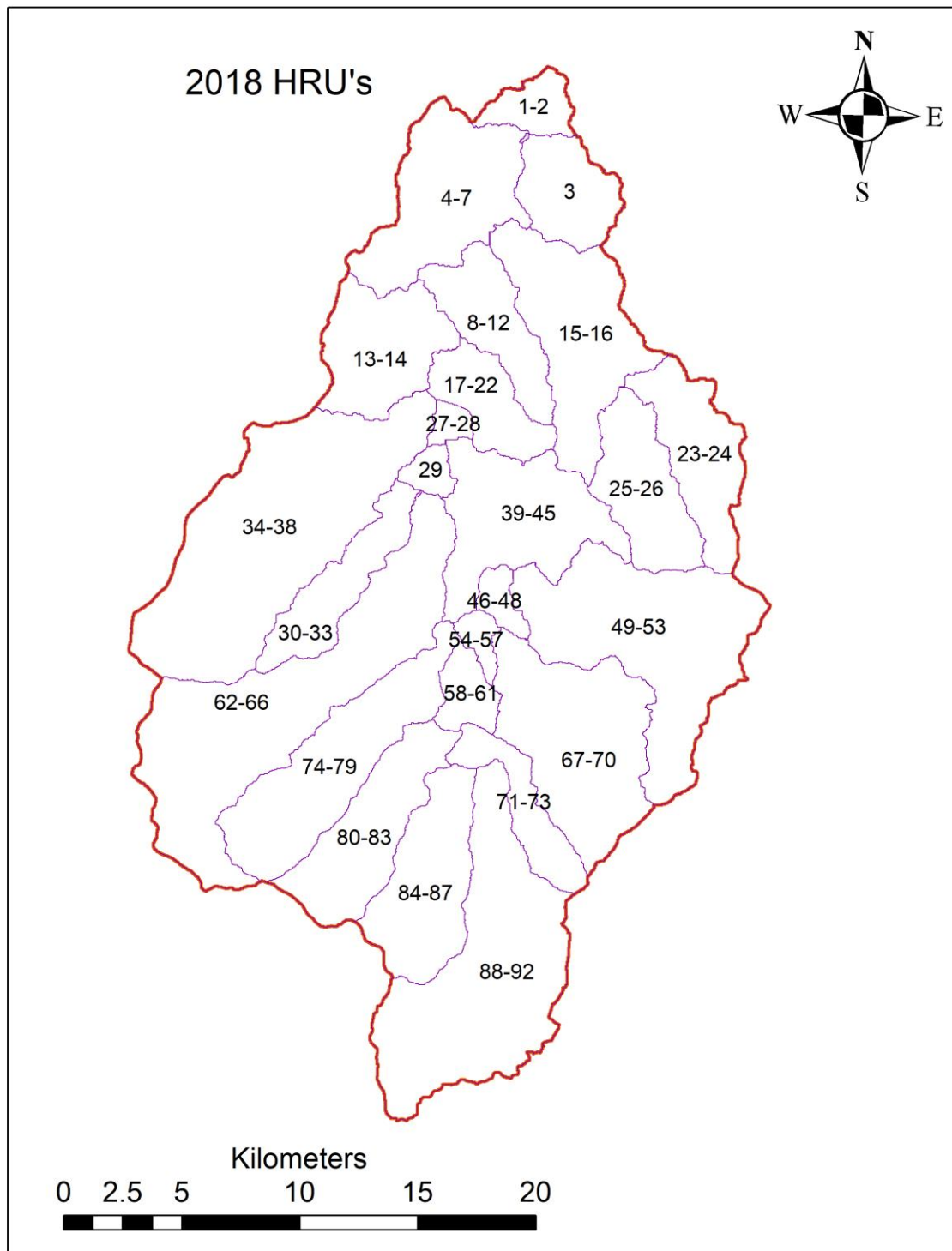


Figure 5.13: HRU's within a catchment using 2018 LULC

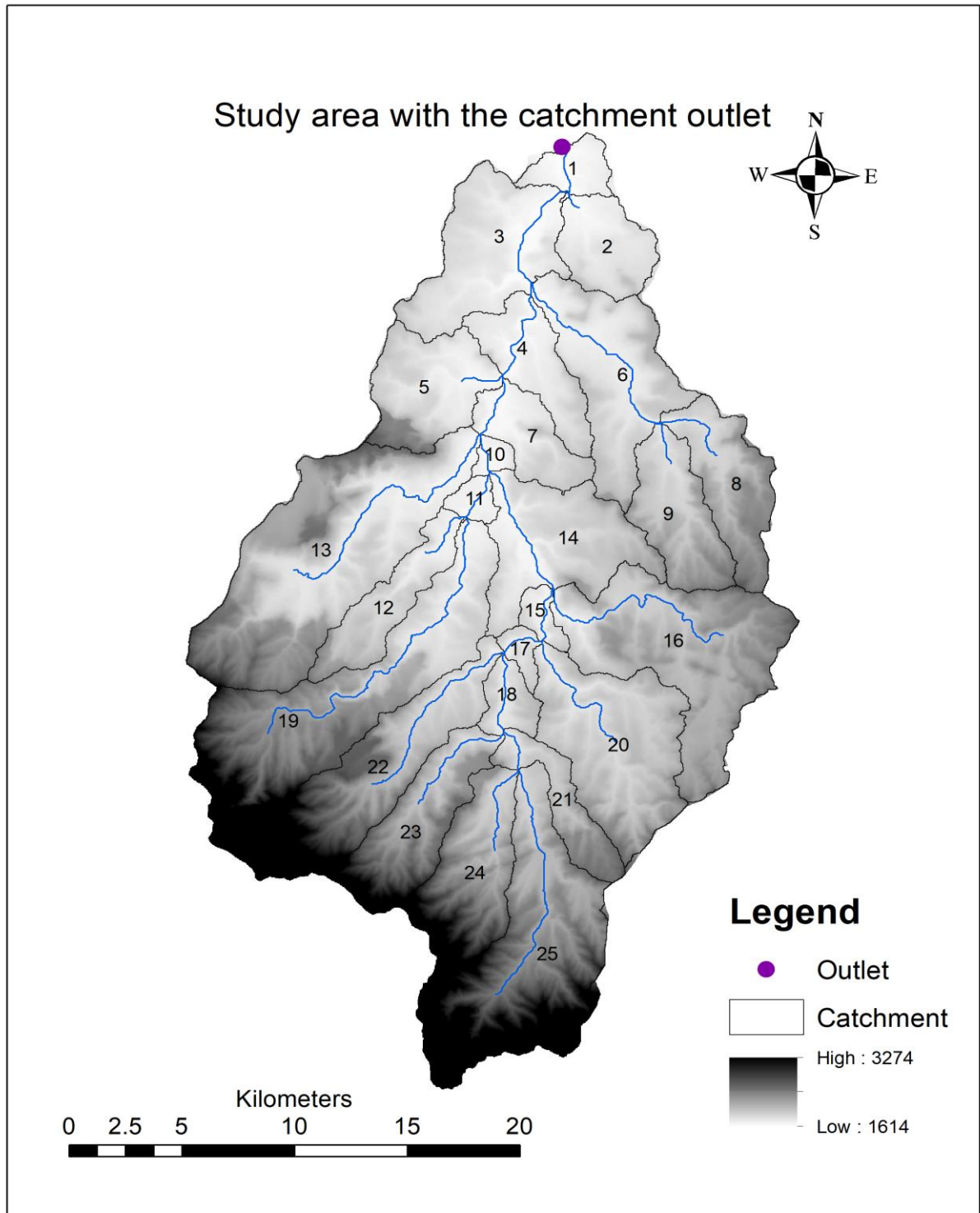


Figure 5.14: Catchment outlet on the study area

The catchment outlet was specified by adding an outlet to the stream flow network at the lowest point of the catchment. It is advantageous to add an outlet to a stream flow measuring station at a recognised location to compare predicted and actual stream flow data. Stream flow data from 1990 to 2018 were available for the new outlet. ArcSWAT was used for modelling of C81F quaternary catchment. The model has

three stages which are catchment delineation, HRU definition and distribution and, weather data definition then run the model. The DEM, soil map and LULC (1990 and 2018) maps were prepared using ArcTools to define the hydrological characteristics were characterised and assigned attributes. The DEM, soil map and LULC (1990 and 2018) maps were sampled to a 30m X 30m resolution. The outlet of the whole catchment was defined during the first stage of catchment delineation. The second stage was when the sub-basin was further subdivided into clusters of homogeneous LULC classes, soil types, slope, and management practices.

Figure 5.15 illustrates the slope distribution in the whole catchment in percentages. The base DEM is used in the slope definition. The user specifies the slope classes with this tool. More HRUs would be produced by more slope classes. The layers were utilised to create the final HRUs after five slope classes were selected. The highest slope is 9999 according to SWAT model. These slope ranges were used to differentiate the topography of the area. The slope range that's dominant in the study area is the 0-20 followed by 20-40 then 40-60 occupying 58.11%, 25.24% and 10.52% respectively.

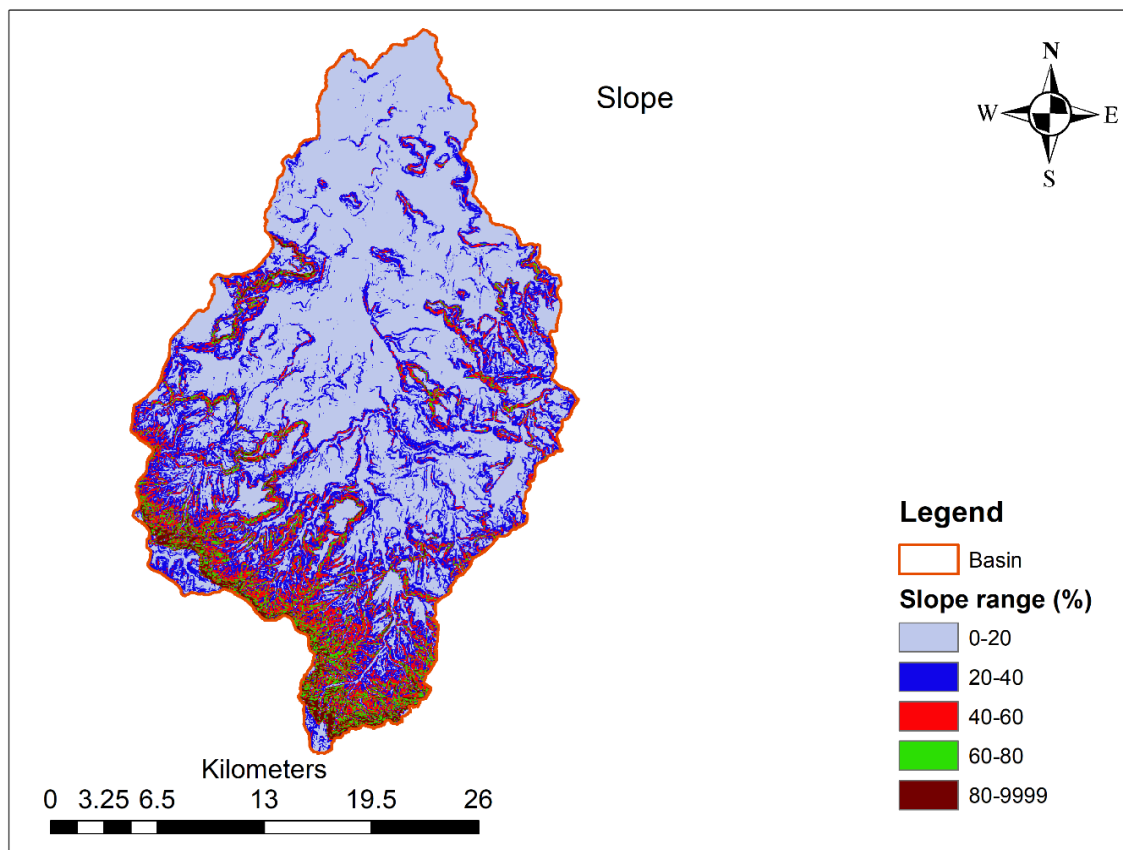


Figure 5.15: Slope distribution in the catchment

Meteorological data was prepared using excel in a format required for ArcSWAT, which are the daily climate variables of precipitation, temperature, relative humidity, wind speed, and solar energy. Observed data for the climate variables was used on SWAT and WGEN generated the other variables that were missing. The model was setup by adding all the data from DEM, LULC, soil, climate data, calculation of surface runoff the SCS-CN method was adopted, PET estimation used the penman-monteith equation and VSR used to model channel water routing. The model was set up to have a three-year warm-up period, to achieve a steady state and mitigate unknown initial conditions for SWAT model. The model results of the LULC, soil and slope distributions in each sub-basin are detailed are on Appendix A and B. Calibration and validation of the model was done using SWAT-CUP and the 2018 LULC map was used due to most changes experienced in this year. The observed flow was prepared from 1993 to 2018. Calibration flow data was from 1993 to 2007 and validation was from 2008 to 2018.

The main factors influencing hydrological processes (such as evapotranspiration, infiltration, surface runoff, and groundwater flow), and consequently, water availability, are climate change and LULC change (Sharma et al., 2022). Water balance is a term that can be used to describe how water enters and exits a system. The water balance equation for a closed system applies the law of conservation of mass, which states that precipitation entering the system is converted into evaporation, transpiration, surface runoff (Juma et al., 2022). The water balance components analysed in this study included the average annual evapotranspiration (ET) surface runoff, lateral flow, and percolation, simulated using 1990 and 2018 LULC maps which are presented in Table 5.10 and Table 5.11 respectively.

The simulated model's maximum percolation value in the 1990 LULC map was 988.00 mm, while its lowest value was 580.70 mm. When compared to the 2018 LULC map, the lowest value was 132.15 mm and the highest was 632.50 mm; this shows that percolation has decreased when using these LULC maps. Based on surface runoff, the 1990 LULC and 2018 LULC are on the rise, with peak values recorded in 2000 and 2011, respectively, at 1116.95 mm and 1854.00 mm. These periods had a lot of precipitation, which might have added to the high amounts of surface runoff. The 1990 LULC indicated an increase in ET during the simulation period, however, the 2018 LULC simulated a decrease in ET. The water balance

component, determined in the 1990 LULC, shows low stream flow and lateral flow due to the predominance of grassland and mixed forest, which causes high percolation. Low annual precipitation was noted in 2015. Percolation, ET, and surface runoff lateral flow were all low in the simulation findings for both periods, despite the ET being lower than the water balance component projected in the 2018 LULC map.

Table 5.10: Average annual water balance components simulation using 1990 LULC C81F quaternary catchment.

Years of simulation	Percolation (mm)	Surface runoff (mm)	Lateral flow (mm)	ET (mm)
1993	682.70	59.45	96.42	519.78
1994	580.70	59.71	121.97	499.20
1995	728.50	325.73	129.23	588.76
1996	988.00	623.06	138.99	859.69
1997	970.60	916.23	136.05	808.12
1998	896.00	522.08	136.77	725.14
1999	714.20	619.96	128.05	666.45
2000	973.22	1116.95	144.44	823.25
2001	837.00	795.25	128.67	735.22
2002	164.00	899.53	129.85	655.66
2003	588.82	669.93	121.24	612.05
2004	661.50	618.83	124.93	633.75
2005	827.00	486.18	133.13	699.53
2006	917.00	410.74	134.61	706.49
2007	705.00	329.09	129.03	622.55
2008	705.50	318.07	126.93	755.81
2009	724.00	627.17	127.54	874.65
2010	910.50	222.21	134.29	718.52
2011	842.00	917.05	149.75	744.15
2012	677.50	719.44	126.62	643.27
2013	583.20	882.72	123.28	586.41
2014	771.00	969.67	132.57	574.85
2015	644.05	516.42	85.46	527.08
2016	643.00	628.39	74.63	686.11
2017	622.60	214.05	61.83	521.82
2018	842.03	118.95	35.55	515.23

Table 5.11: Average annual water balance components simulation using 2018 LULC C81F quaternary catchment.

Years of simulation	Percolation (mm)	Surface runoff (mm)	Lateral flow(mm)	ET (mm)
1993	335.34	100.20	79.97	573.00
1994	357.27	345.00	112.23	483.70
1995	500.40	589.00	98.42	523.56
1996	505.87	875.00	118.64	700.88
1997	497.25	1657.00	117.63	675.39
1998	443.56	786.00	119.04	560.72
1999	383.68	735.00	113.02	552.39
2000	469.74	1425.00	119.77	664.00
2001	487.71	970.00	116.72	607.91
2002	334.84	1075.00	115.71	593.39
2003	410.88	856.00	119.61	540.73
2004	345.41	754.00	111.05	568.61
2005	261.80	647.00	89.47	624.75
2006	388.22	565.00	112.09	625.21
2007	357.08	499.00	111.82	561.20
2008	311.23	373.16	110.17	562.43
2009	414.07	975.65	114.41	615.13
2010	632.50	478.50	120.15	608.45
2011	440.83	1854.00	114.85	605.94
2012	534.07	997.54	119.02	526.70
2013	396.95	1125.00	113.33	523.55
2014	419.27	1765.00	115.63	500.65
2015	319.06	768.00	79.97	491.31
2016	410.41	712.50	80.53	525.00
2017	229.78	498.36	57.46	521.74
2018	132.15	127.04	39.48	483.50

The LULC classes were further subdivided into 25 sub-basins and 92 HRUs using a 2018 LULC. Pasture is 100% on 10 of the sub-basins (Table 5.12), these show no change in LULC class for using both 1990 and 2018 LULC. This LULC class was dominant in 1990 but reduced with time due to many factors in the study area.

Table 5.12: Sub-basins with 100% of pasture as a LULC class

Sub-basin Number	HRU number (1990)	HRU number (2018)
2	3	3
5	11-12	13-14
6	13-14	15-16
8	19-20	23-24
9	21-22	25-26
16	47-51	49-53
21	73-76	72-74
23	79-82	81-84
24	83-86	85-88
25	87-90	89-92

5.5.1 Discussion

This section analyses the impact of LULC changes on water balance for the period of 1990 to 2018. The components of the water balance were represented by two LULC maps, from 1990 and 2018 because most of the changes took place for 28 years. There were 25 sub-basins and 90 HRUs in Appendix C of the 1990 LULC, and there were 25 sub-basins and 92 HRUs in Appendix D of the 2018 LULC. The slope and soil parameters remain the same for both years only the LULC data changes for each sub-basin. Annexure C details the number of HRU's in each sub-basin and what type of LULC classes are taking place together with the soil and slope.

The study area experienced three LULC classes that were modelled for most of the sub-basin, namely pasture, generic agricultural land and urban. Sub-basin 1 shows 61.38 % of pasture and 39.34% generic agricultural land for 1990, where pasture decreased to 54.67 % and agriculture increased by 6.71. Pasture covered the whole sub-basin 3 & 7 in 1990 and decreased to 75.19% with 25.53% of the area used for generic agricultural land and 60% was cleared for urban (commercial, industrial, and housing). Generic agricultural land increased from 25.06% to 34.15% in sub-basin 4, 1990 to 2018 respectively. Sub-basin 10 experienced a clear out of pasture from 38.71% to 0% in 2018, and the new land was used for agriculture. Sub-basin 11 experienced a total clear out of pasture from 38.71% and the land was 100% urban. Slight increase in urban area took place in other sub-basins. These three LULC classes have a huge impact on water balance components in the study area. The

summary of the water balance components for the years 1990 and 2018 is shown in Appendix E and F.

Surface runoff has increased in the 2018 LULC, when compared to the 1990 LULC. This increase in surface runoff is due to the increase in urban area whereby pasture and mixed forest has been replaced by impervious surfaces such as buildings, roads, pavements which in return prevent water from infiltrating into the ground. Impervious surfaces cause rainfall to runoff quickly in drainage systems, rivers, streams, and dams. Therefore, high peak flows in rivers, streams will be experienced during storm events. Increase runoff in urban areas can carry pollutants such as grease, heavy metals, oil and nutrients from roads, industries and rooftop, these pollutants will contaminate surface waters, degrade water quality for agriculture and harm aquatic ecosystems.

A decrease in pasture and the increase in barren land are linked which is seen for the period of 28 years, both are linked to an increase in surface runoff because there's more space for water to flow. In addition, the dominant LULC classes in 28 years is pasture and it's linked with the decrease in mixed forest which may further be connected to the decrease in evapotranspiration and infiltration. Increased surface albedo, decreased surface aerodynamic roughness, decreased leaf area, and shallower rooting depth brought on by the conversion of forest to pasture may also result in decreased evapotranspiration (Anand et al., 2018). The catchment experiences an increase in urban area which has negatively impacted on water balance component such as evapotranspiration. Urbanisation, or the growth of built-up areas, will result in less vegetation cover and less evapotranspiration. The increase in urban has a negative impact on ET due to the removal of soil surface, vegetation which decreases the amount of water availability for evaporation and transpiration. The expansion in urban area disrupts natural drainage patterns where construction of roads, buildings and other infrastructure can cause changes on drainage patterns and potentially increase localised flooding, stormwater drains and culverts when not properly design and maintained have a negative impact on the lateral flow. Percolation decreased due to pervious surfaces such as soil and natural vegetation replaced with impervious surface such as concrete and asphalt, which results more surface runoff that infiltration.

The increase in generic agricultural land contributes to the increase in surface runoff, when pasture and mixed forest is replaced with crops, results in fewer plants to intercept rainfall which slows down water movement on the surface. The irrigation and ploughing compact the soil at times reducing the infiltration rate because the soil will be moist in most times. The decrease in percolation can be due to excessive irrigation or poor soil management practices which leads to waterlogging, soil compaction, and reduced percolation rates.

The present research evaluated the effects of various scenarios for changing LULC on the elements of the water balance are crucial for making decisions. The findings of this study suggest that SWAT can be a useful tool for predicting how changes in LULC affects C81F quaternary catchments' water balance at a reasonable cost and the catchment's water balance was severely impacted by the observed changes in LULC. The combination of circumstances that could exist in the future and the actual response of the catchment to these combinations of scenarios are both uncertain, as are future LULC and climate. However, such scenario analysis in modelling enables comprehension of the likely effects of land use or climate change at a catchment scale.

For example, the sub-basin 11 and HRU 29 were 100% covered by urban area. This shows that the area is experiencing more urban and development. According to Mocwagae (2020), the district experienced an increase in population from 736,812 (2018) to 739,305 (2019). Also, the district has been expanding at a 0.5% annual rate, which is less than the provincial (0.6%) and federal (1.5%) rates. One factor influencing change in this regard is the need for urban sites brought on by the growth in population. Complexity was discovered to be added to the hydrological response by urbanisation (Botai et al., 2016). As the number of impermeable regions rises, some of the rainfall's evaporation and transpiration portions are diverted near runoff, increasing the volume of runoff. (Schütte & Schulze, 2017).

5.6 The mitigation strategies for the limited water resources in C81F quaternary catchment

This section presents the result that responded to the third sub-question that focused on which strategies can be implemented for the limited water resources in the quaternary catchment. This is because the decrease of pasture in the C81F

quaternary catchment needs immediate attention to manage it. Thabo Mofutsanyana district has a lot of farmers who need pastures for their livestock. This had led some farmers to cultivate pastures of their own for their livestock to survive (Venter, 2021). Again, different crops are typically rotated to increase soil fertility according to a rotation policy (Muyambo et al., 2023).

The increase in generic agricultural land needs a management strategy so that it can keep on increasing (Botai et al., 2016). The main economic sectors in the Thabo Mofutsanyana district municipality are agriculture and tourism (Muyambo et al., 2023). Notably, the inclusion of black farmers in the sector is hampered by the slow pace of land reform. Although assistance is offered, beginner farmers have trouble getting information and assistance from the Department of Agriculture. People require on-the-ground instruction and ongoing supervision. There was a strong belief that farms should only be sold to individuals who had a genuine interest in farming and that new farmers should be identified using strict criteria. It is important to investigate and implement support programs that will benefit both established farmers and those just starting out. Recent communal and small-scale farming initiatives failed owing to a lack of dedication, management, and other skills.

The water demand of different land types such as generic agricultural land, pasture, and mixed forested is different. Generic agricultural land requires irrigation which causes the water demand to be high. The model simulations show an increase in surface runoff from 1990 to 2018 by 4.24 mm. This is connected to the decrease in pasture and mixed forest, and the increase in urban areas. Evapotranspiration (ET), a key component of the soil water balance, is vital in calculating prospective yields in the agricultural sector. For a specific soil textural class and agro-climatic conditions, ET always exhibit similar behaviour despite being influenced by numerous variables, including soil moisture, soil temperature, and vapour pressure gradients (Bhatt & Hossain, 2019). The value of evapotranspiration therefore needs to be calculated to help irrigators in relation to how much water will be needed.

The following strategies needs to be implemented in the municipality:

- Rainwater harvesting for irrigation (agriculture), livestock and domestic uses. This will involve collecting water from roofs and using surface runoff for different

uses, this could help since the quaternary catchment is semi-arid and its upstream.

- Wastewater to be re-used from treatment works.
- The use of grey water from households.
- Training and support for new farmers and existing farmers about how to do farm rotation, managing a farm and financial support will be beneficial.
- Agricultural sector needs on ground and ongoing supervision, and crop rotation is the best option for different seasons.
- Pastures management in the catchment area is very crucial to preserve it for future use and not to be used inconsiderably. Rules and regulations need to be in place for cutting of pasture in the area. The decrease in pasture is very alarming.

5.7 Chapter Summary

This chapter presented the results and discussions relating to the three research objectives of this study. Firstly, the results and discussion of the impact of LULC changes for a period of 28 years were presented. This was followed by the results and discussions addressing the impact of LULC changes on water resources, and ArcSWAT was used for modelling whilst SWAT-CUP was used to calibrate and validate the results. Water balance is undoubtedly impacted by LULC changes in the catchment, but stream water quality is likely to be most affected. Lastly, the results and discussion of the mitigation and adaptation strategies for the stakeholders around the study were presented. The next chapter will present the conclusions and recommendations for future research.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter presents the conclusion and recommendations of the study. This study was aimed at evaluating the impact of LULC changes on the water resources in the C81F quaternary catchment by applying remotely sensed data such as satellite imagery, in conjunction with ArcGIS and the SWAT model. Thus, the conclusion of the study is presented, and the recommendations are made at the end of the chapter.

6.2 Conclusion of the Study

It is widely reported that water is a scarce resource in South Africa and the country is classified as water-stressed owing to erratic rainfall patterns caused by climate change and variability. In the wake of all this, water demand remains very high, and it is not met by its supply. In South Africa, the scarcity of freshwater is decreasing in quality owing to the destruction of river catchments and an increase in unabated pollution activity evolving from the destruction of wetlands, damming of rivers, deforestation, and rising urbanisation. As a result, the aim of this study is to evaluate the impact of LULC changes on the water resources in C81F quaternary catchment. In this regard, remote sensing, GIS, and computer-based hydrologic simulation models such as the SWAT model were used.

Hydrologic systems are heterogeneous, and model inputs like land, and soil land use/cover exhibit significant spatial variability. It requires time to create the input files for such a model for large catchments. Water balance experts may be able to conduct basin-scale analyses of water availability and water quality with a great deal less time and expenditure because of the SWAT model and its GIS bounds. The DEM was used to divide the C81F quaternary catchment into 25 separate sub-basins based on reaches (streams), which were then divided into 90 and 92 HRUs for using 1990 and 2018 LULC. The designated catchment spans 67665.24 ha in total.

Determining the changes of LULC for a period of 28 years was the first objective. The changes in LULC have an impact on the catchment's water balance. LULC maps are one of the inputs on the SWAT model. The difference between the LULC maps of the same scene at various times is described and quantified by the change detection evaluation. To determine the area of various land cover types and to identify changes

that take place within the data range, the classified LULC maps of the four different periods are employed. Most changes occurred between 2010 to 2018 (8 years) and 1990 to 2018 (28 years). The change was a linear pattern. Between 2010 and 2018, there were positive changes seen at rates of 354.30 ha, 260.04 ha, and 124.69 ha for the increasing LULC classes, which include generic agriculture, barren land, and urban. The negative rate of change for the period of 8 years is mixed forest, pasture, and wetlands mixed decrease with 391.88 ha, 316.95 ha and 31.29 ha respectively. On the other hand, during the 28 years between 1990 and 2018, the majority of changes happened at a rate of 104.30 ha, 84.70 ha, and 48.77 ha, with positive rates of change happening in urban areas, barren land, and generic agricultural land. For wetlands mixed, mixed forest, and pasture, the corresponding negative rates of change are 11.67 ha, 78.63 ha, and 148.40 ha. The two transitional periods were compared, and it was found that the 1990 to 2018 period saw the most changes. To further show the changes pasture dominated the LULC in 1990, followed by urban, then mixed forest which accounted for 71.44%, 16.73% and 5.50% of the total area, respectively. The least dominant classes were water and barren land. Whereas, for 2018, the dominant LULC was pasture, urban, then generic agricultural land, comprising 65.08%, 18.82% and 7.96% of the total area, respectively.

Objective number 2 was accomplished by using ArcSWAT, the model simulation was executed successfully using the LULC maps for 1990 and 2018. Water balance components using these two maps were modelled. Insight into how to provide useful details in catchments where there is little data available came from the evaluation of the SWAT hydrological model and examination of its capacity to accurately simulate the various elements of the water balance in general and stream flow using various efficiency criteria. Pasture, generic agricultural land and urban after modelling were concluded to have more impact on water balance components.

The increase in urban development impacts water balance by reducing evapotranspiration and percolation due to reduced pasture and mixed forest. It disrupts natural drainage patterns, potentially increasing flooding. The replacement of pervious surfaces with impervious surface such as buildings and roads results in more surface runoff than infiltration, leading to decreased lateral flow. Impervious surfaces cause rainfall to runoff quickly in drainage systems, rivers, streams, and dams. Therefore, high peak flows in rivers, streams will be experienced during storm

events. Increase runoff in urban areas can carry pollutants such as grease, heavy metals, oil and nutrients from roads, industries and rooftop, these pollutants will contaminate surface waters.

Increased generic agricultural land leads to increased surface runoff due to fewer plants intercepting rainfall and compacted soil during irrigation and ploughing. The decrease in percolation can be due to excessive irrigation or poor soil management practices which leads to waterlogging, soil compaction, and reduced percolation rates. A decrease in pasture and the increase in barren land are linked which is seen for the period of 28 years, both are linked to an increase in surface runoff because there's more space for water to flow which may further be connected to the decrease in evapotranspiration, percolation, and infiltration.

The effectiveness and applicability of the ArcSWAT model were evaluated in the research area using model calibration, model validation, and scenario analysis. The model simulated flows were compared against measured flow data at the catchment's outlet. Therefore, SWAT's effectiveness was assessed statistically and graphically. The statistics efficiency criteria were implemented using percent bias (PBIAS), Nash and Sutcliffe (NSE), and correlation coefficient (R^2).

The simulated flow trends correlate with the observed flow trends within the permissible calibration criteria ranges where R^2 , NSE and PBIAS ranged from 0.79, 0.70 and -3.6. However, the calibration results were also good with R^2 , NSE and PBIAS at 0.72, 0.69 and 10, respectively. After calibration and validation, it was seen that the results were satisfactory. Given the positive outcomes of SWAT in this study and the model's thoroughness in representing land surface procedures, the model is very promising for studies of land and water management and is anticipated to provide managers of land and water resources with useful information. This model has therefore proven to work well in semi-arid areas.

Objective number 3 is accomplished by developing the mitigation strategies which are: rainwater harvesting for irrigation, livestock and domestic uses, wastewater to be re-used from treatment works, the use of grey water from households, training, and support for farmers (new and existing), agricultural supervision (ground and on-going), crop rotation, pasture management.

6.3 Recommendations

It is recommended that more studies should be done on this catchment to assess the potential impacts of other water balance components, such as evapotranspiration, possible increase in abstraction, groundwater, and climate change on the runoff. Analysis of future hydrology and water resources of the region is needed. For example, the erosion application of the model needs to be done, by creating a comprehensive soil map of the study area before using the model to predict erosion. Also, it is advised to obtain a sizable amount of observed data that matches the land use/cover of the study area for the model's calibration and validation to capture trends in water quality. Although assistance is offered, beginner farmers have trouble getting information and assistance from the Department of Agriculture. People therefore require on-the-ground instruction and ongoing supervision.

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APPENDICES

Appendix A: Study area topographic report generated by ArcSWAT for LULC 1990

Watershed		Area [ha]	Area[acres]		
Number of Subbasins: 25		67654.2600	167177.0592		
		Area [ha]	Area[acres]	%Wat.Area	
LANDUSE:					
	Water --> WATR	163.8010	404.7605	0.24	
	Wetlands-Mixed --> WETL	1101.4644	2721.7735	1.63	
	Mixed forest --> FRST	3267.1367	8073.2583	4.83	
	Pasture --> PAST	48685.8852	120305.2566	71.96	
	Agricultural Land-Generic --> AGR	2355.1268	5819.6361	3.48	
	Barren land --> BARR	701.0720	1732.3839	1.04	
	Urban --> URB	11379.7740	28119.9904	16.82	
SOILS:					
	Fr20-3bc-575	83.2149	205.6282	0.12	
	I-Bc-L-2--640	51897.5453	128241.4294	76.71	
	Ws13-2ab-985	15673.4998	38730.0016	23.17	
SLOPE:					
	0-20	39479.7606	97556.4625	58.36	
	20-40	16985.3582	41971.6695	25.11	
	40-60	7097.2885	17537.7547	10.49	
	60-80	2642.2998	6529.2549	3.91	
	80-9999	1449.5528	3581.9176	2.14	
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	1	756.8100	1870.1154	1.12	
LANDUSE:					
	Wetlands-Mixed --> WETL	19.3987	47.9351	0.03	2.56
	Mixed forest --> FRST	1.8130	4.4799	0.00	0.24
	Pasture --> PAST	449.1611	1109.8994	0.66	59.35
	Agricultural Land-Generic --> AGR	287.8982	711.4108	0.43	38.04
	Barren land --> BARR	3.9885	9.8558	0.01	0.53
SOILS:					
	Ws13-2ab-985	762.2594	1883.5811	1.13	100.72
SLOPE:					
	0-20	759.0867	1875.7412	1.12	100.30
	20-40	3.1727	7.8399	0.00	0.42

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	2	1609.5600	3977.3032	2.38	
LANDUSE:					
	Water --> WATR	3.8979	9.6318	0.01	0.24
	Wetlands-Mixed --> WETL	5.0763	12.5438	0.01	0.32
	Mixed forest --> FRST	32.5426	80.4145	0.05	2.02
	Pasture --> PAST	1302.1591	3217.7003	1.92	80.90
	Agricultural Land-Generic --> AGRL	212.8416	525.9422	0.31	13.22
	Barren land --> BARR	49.3125	121.8537	0.07	3.06
	Urban --> URBN	15.3195	37.8553	0.02	0.95
SOILS:					
	Ws13-2ab-985	1621.1496	4005.9417	2.40	100.72
SLOPE:					
	0-20	1477.9257	3652.0283	2.18	91.82
	20-40	129.4454	319.8661	0.19	8.04
	40-60	13.5066	33.3754	0.02	0.84
	60-80	0.2719	0.6720	0.00	0.02
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	3	3414.3300	8436.9801	5.05	
LANDUSE:					
	Water --> WATR	0.1813	0.4480	0.00	0.01
	Wetlands-Mixed --> WETL	111.0439	274.3949	0.16	3.25
	Mixed forest --> FRST	9.6993	23.9676	0.01	0.28
	Pasture --> PAST	2767.7567	6839.2651	4.09	81.06
	Agricultural Land-Generic --> AGRL	522.7673	1291.7840	0.77	15.31
	Barren land --> BARR	20.2145	49.9511	0.03	0.59
	Urban --> URBN	7.2518	17.9197	0.01	0.21
SOILS:					
	I-Bc-L-2--640	2256.5017	5575.9286	3.34	66.09
	Ws13-2ab-985	1182.4131	2921.8018	1.75	34.63
SLOPE:					
	0-20	3221.0875	7959.4684	4.76	94.34
	20-40	202.1451	499.5107	0.30	5.92
	40-60	15.0476	37.1833	0.02	0.44
	60-80	0.6345	1.5680	0.00	0.02

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	4	1831.9500	4526.8400	2.71	
LANDUSE:					
	Water --> WATR	3.1727	7.8399	0.00	0.17
	Wetlands-Mixed --> WETL	66.9889	165.5329	0.10	3.66
	Mixed forest --> FRST	13.4159	33.1514	0.02	0.73
	Pasture --> PAST	1303.5189	3221.0603	1.93	71.15
	Agricultural Land-Generic --> AGRL	431.8473	1067.1162	0.64	23.57
	Barren land --> BARR	19.1267	47.2631	0.03	1.04
	Urban --> URBN	7.0705	17.4717	0.01	0.39
SOILS:					
	I-Bc-L-2--640	1298.6239	3208.9645	1.92	70.89
	Ws13-2ab-985	546.5170	1350.4710	0.81	29.83
SLOPE:					
	0-20	1663.4822	4110.5478	2.46	90.80
	20-40	159.3593	393.7847	0.24	8.70
	40-60	20.0332	49.5031	0.03	1.09
	60-80	2.2662	5.5999	0.00	0.12
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	5	2437.7400	6023.7774	3.60	
LANDUSE:					
	Water --> WATR	0.1813	0.4480	0.00	0.01
	Wetlands-Mixed --> WETL	67.6234	167.1009	0.10	2.77
	Mixed forest --> FRST	105.8769	261.6271	0.16	4.34
	Pasture --> PAST	2146.1831	5303.3256	3.17	88.04
	Agricultural Land-Generic --> AGRL	84.9372	209.8841	0.13	3.48
	Barren land --> BARR	30.6390	75.7106	0.05	1.26
	Urban --> URBN	19.8519	49.0551	0.03	0.81
SOILS:					
	I-Bc-L-2--640	2455.2929	6067.1515	3.63	100.72
SLOPE:					
	0-20	1956.7286	4835.1743	2.89	80.27
	20-40	387.7017	958.0302	0.57	15.90
	40-60	63.2723	156.3491	0.09	2.60
	60-80	19.0361	47.0391	0.03	0.78
	80-9999	28.5541	70.5587	0.04	1.17

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	6	3648.9600	9016.7626	5.39	
LANDUSE:					
	Wetlands-Mixed --> WETL	22.2994	55.1030	0.03	0.61
	Mixed forest --> FRST	139.2354	344.0576	0.21	3.82
	Pasture --> PAST	3219.0933	7954.5405	4.76	88.22
	Agricultural Land-Generic --> AGRL	229.4302	566.9335	0.34	6.29
	Barren land --> BARR	33.7211	83.3265	0.05	0.92
	Urban --> URBN	31.4549	77.7266	0.05	0.86
SOILS:					
	I-Bc-L-2--640	350.5360	866.1919	0.52	9.61
	Ws13-2ab-985	3324.6983	8215.4956	4.91	91.11
SLOPE:					
	0-20	2910.9806	7193.1786	4.30	79.78
	20-40	623.8398	1541.5394	0.92	17.10
	40-60	123.4626	305.0823	0.18	3.38
	60-80	13.3253	32.9274	0.02	0.37
	80-9999	3.6259	8.9598	0.01	0.10
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	7	1424.7000	3520.5049	2.11	
LANDUSE:					
	Water --> WATR	0.4532	1.1200	0.00	0.03
	Wetlands-Mixed --> WETL	75.2379	185.9166	0.11	5.28
	Mixed forest --> FRST	34.4463	85.1184	0.05	2.42
	Pasture --> PAST	1205.8003	2979.5927	1.78	84.64
	Agricultural Land-Generic --> AGRL	0.4532	1.1200	0.00	0.03
	Barren land --> BARR	14.3224	35.3913	0.02	1.01
	Urban --> URBN	104.2452	257.5952	0.15	7.32
SOILS:					
	I-Bc-L-2--640	1140.4430	2818.0917	1.69	80.05
	Ws13-2ab-985	294.5155	727.7625	0.44	20.67
SLOPE:					
	0-20	1224.7457	3026.4079	1.81	85.97
	20-40	189.4544	468.1513	0.28	13.30
	40-60	20.5771	50.8471	0.03	1.44
	60-80	0.1813	0.4480	0.00	0.01

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	8	2234.6100	5521.8330	3.30	
LANDUSE:					
	Wetlands-Mixed --> WETL	3.8072	9.4078	0.01	0.17
	Mixed forest --> FRST	138.9634	343.3856	0.21	6.22
	Pasture --> PAST	2026.1650	5006.7551	2.99	90.67
	Agricultural Land-Generic --> AGRL	41.0636	101.4701	0.06	1.84
	Barren land --> BARR	24.9282	61.5989	0.04	1.12
	Urban --> URBN	15.7728	38.9753	0.02	0.71
SOILS:					
	Fr20-3bc-575	59.9184	148.0613	0.09	2.68
	I-Bc-L-2--640	1.5410	3.8079	0.00	0.07
	Ws13-2ab-985	2189.2409	5409.7237	3.24	97.97
SLOPE:					
	0-20	1289.5591	3186.5649	1.91	57.71
	20-40	729.5354	1802.7186	1.08	32.65
	40-60	182.2932	450.4556	0.27	8.16
	60-80	40.6103	100.3501	0.06	1.82
	80-9999	8.7022	21.5036	0.01	0.39

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	9	2182.6800	5393.5114	3.23	
LANDUSE:					
	Wetlands-Mixed --> WETL	11.6936	28.8955	0.02	0.54
	Mixed forest --> FRST	129.0828	318.9701	0.19	5.91
	Pasture --> PAST	1878.5900	4642.0899	2.78	86.07
	Agricultural Land-Generic --> AGRL	142.5894	352.3455	0.21	6.53
	Barren land --> BARR	32.1801	79.5185	0.05	1.47
	Urban --> URBN	4.2605	10.5278	0.01	0.20
SOILS:					
	Ws13-2ab-985	2198.3963	5432.3472	3.25	100.72
SLOPE:					
	0-20	1247.0451	3081.5108	1.84	57.13
	20-40	718.1138	1774.4951	1.06	32.90
	40-60	189.4544	468.1513	0.28	8.68
	60-80	36.4405	90.0463	0.05	1.67
	80-9999	7.3425	18.1437	0.01	0.34

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	10	256.5000	633.8243	0.38	
LANDUSE:					
	Water --> WATR	0.2719	0.6720	0.00	0.11
	Wetlands-Mixed --> WETL	36.4405	90.0463	0.05	14.21
	Mixed forest --> FRST	2.0849	5.1519	0.00	0.81
	Pasture --> PAST	83.5775	206.5242	0.12	32.58
	Barren land --> BARR	2.0849	5.1519	0.00	0.81
	Urban --> URBN	133.8872	330.8419	0.20	52.20
SOILS:					
	I-Bc-L-2--640	258.3469	638.3882	0.38	100.72
SLOPE:					
	0-20	250.6418	619.3485	0.37	97.72
	20-40	7.6144	18.8157	0.01	2.97
	40-60	0.0906	0.2240	0.00	0.04
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	11	360.8100	891.5796	0.53	
LANDUSE:					
	Wetlands-Mixed --> WETL	38.4348	94.9742	0.06	10.65
	Mixed forest --> FRST	0.2719	0.6720	0.00	0.08
	Pasture --> PAST	94.3646	233.1797	0.14	26.15
	Barren land --> BARR	2.0849	5.1519	0.00	0.58
	Urban --> URBN	228.2518	564.0215	0.34	63.26
SOILS:					
	I-Bc-L-2--640	363.4080	897.9993	0.54	100.72
SLOPE:					
	0-20	358.6037	886.1276	0.53	99.39
	20-40	4.8043	11.8718	0.01	1.33

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	12	1726.0200	4265.0817	2.55	
LANDUSE:					
	Wetlands-Mixed --> WETL	54.6608	135.0695	0.08	3.17
	Mixed forest --> FRST	10.2432	25.3115	0.02	0.59
	Pasture --> PAST	450.1582	1112.3634	0.67	26.08
	Barren land --> BARR	19.6706	48.6071	0.03	1.14
	Urban --> URBN	1203.7154	2974.4408	1.78	69.74
SOILS:					
	I-Bc-L-2--640	1738.4482	4295.7923	2.57	100.72
SLOPE:					
	0-20	1320.5607	3263.1715	1.95	76.51
	20-40	351.9863	869.7759	0.52	20.39
	40-60	48.8593	120.7338	0.07	2.83
	60-80	8.7022	21.5036	0.01	0.50
	80-9999	8.3396	20.6076	0.01	0.48

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	13	7559.8200	18680.6932	11.17	
LANDUSE:					
	Water --> WATR	2.9914	7.3919	0.00	0.04
	Wetlands-Mixed --> WETL	287.8982	711.4108	0.43	3.81
	Mixed forest --> FRST	417.7968	1032.3969	0.62	5.53
	Pasture --> PAST	4195.8259	10368.0957	6.20	55.50
	Agricultural Land-Generic --> AGRL	131.6210	325.2420	0.19	1.74
	Barren land --> BARR	56.9270	140.6694	0.08	0.75
	Urban --> URBN	2491.2802	6156.0778	3.68	32.95
SOILS:					
	I-Bc-L-2--640	7584.3404	18741.2844	11.21	100.32
SLOPE:					
	0-20	4340.9535	10726.7130	6.42	57.42
	20-40	2209.0021	5458.5548	3.27	29.22
	40-60	735.3369	1817.0543	1.09	9.73
	60-80	190.7235	471.2873	0.28	2.52
	80-9999	108.3244	267.6750	0.16	1.43

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	14	3337.6500	8247.5000	4.93	
LANDUSE:					
	Wetlands-Mixed --> WETL	73.6062	181.8846	0.11	2.21
	Mixed forest --> FRST	71.3400	176.2847	0.11	2.14
	Pasture --> PAST	1119.7753	2767.0207	1.66	33.55
	Barren land --> BARR	66.0824	163.2930	0.10	1.98
	Urban --> URBN	2030.8787	5018.4029	3.00	60.85
SOILS:					
	I-Bc-L-2--640	1688.9543	4173.4906	2.50	50.60
	Ws13-2ab-985	1672.7283	4133.3953	2.47	50.12
SLOPE:					
	0-20	2683.9979	6632.2930	3.97	80.42
	20-40	504.4564	1246.5369	0.75	15.11
	40-60	137.3318	339.3537	0.20	4.11
	60-80	26.3786	65.1828	0.04	0.79
	80-9999	9.5180	23.5196	0.01	0.29

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	15	389.2500	961.8562	0.58	
LANDUSE:					
	Wetlands-Mixed --> WETL	20.0332	49.5031	0.03	5.15
	Mixed forest --> FRST	4.0792	10.0798	0.01	1.05
	Pasture --> PAST	267.6837	661.4597	0.40	68.77
	Barren land --> BARR	3.6259	8.9598	0.01	0.93
	Urban --> URBN	96.6308	238.7796	0.14	24.82
SOILS:					
	I-Bc-L-2--640	392.0528	968.7820	0.58	100.72
SLOPE:					
	0-20	312.9170	773.2337	0.46	80.39
	20-40	69.8896	172.7008	0.10	17.95
	40-60	8.0677	19.9356	0.01	2.07
	60-80	1.1784	2.9119	0.00	0.30

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	16	5554.7100	13725.9661	8.21	
LANDUSE:					
	Water --> WATR	45.7773	113.1179	0.07	0.82
	Wetlands-Mixed --> WETL	15.3195	37.8553	0.02	0.28
	Mixed forest --> FRST	509.3514	1258.6327	0.75	9.17
	Pasture --> PAST	4469.2204	11043.6672	6.61	80.46
	Barren land --> BARR	100.0754	247.2914	0.15	1.80
	Urban --> URBN	364.0425	899.5673	0.54	6.55
SOILS:					
	Fr20-3bc-575	23.2965	57.5669	0.03	0.42
	I-Bc-L-2--640	3598.9086	8893.0830	5.32	64.79
	Ws13-2ab-985	1881.5814	4649.4818	2.78	33.87
SLOPE:					
	0-20	3076.8665	7603.0910	4.55	55.39
	20-40	1766.6397	4365.4550	2.61	31.80
	40-60	524.1270	1295.1440	0.77	9.44
	60-80	114.5791	283.1307	0.17	2.06
	80-9999	21.5742	53.3110	0.03	0.39
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	17	323.9100	800.3978	0.48	
LANDUSE:					
	Wetlands-Mixed --> WETL	1.8130	4.4799	0.00	0.56
	Mixed forest --> FRST	6.1641	15.2317	0.01	1.90
	Pasture --> PAST	178.5766	441.2718	0.26	55.13
	Agricultural Land-Generic --> AGR	41.7887	103.2621	0.06	12.90
	Barren land --> BARR	0.9065	2.2400	0.00	0.28
	Urban --> URBN	96.9934	239.6756	0.14	29.94
SOILS:					
	I-Bc-L-2--640	326.2423	806.1610	0.48	100.72
SLOPE:					
	0-20	246.0188	607.9247	0.36	75.95
	20-40	71.3400	176.2847	0.11	22.02
	40-60	8.7929	21.7276	0.01	2.71
	60-80	0.0906	0.2240	0.00	0.03

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	18	698.4900	1726.0037	1.03	
LANDUSE:					
	Water --> WATR	0.1813	0.4480	0.00	0.03
	Wetlands-Mixed --> WETL	5.6202	13.8877	0.01	0.80
	Mixed forest --> FRST	17.7670	43.9032	0.03	2.54
	Pasture --> PAST	458.4978	1132.9710	0.68	65.64
	Agricultural Land-Generic --> AGRL	32.5426	80.4145	0.05	4.66
	Barren land --> BARR	2.4475	6.0479	0.00	0.35
	Urban --> URBN	186.4630	460.7595	0.28	26.70
SOILS:					
	I-Bc-L-2--640	703.5195	1738.4318	1.04	100.72
SLOPE:					
	0-20	489.8620	1210.4735	0.72	70.13
	20-40	191.1767	472.4072	0.28	27.37
	40-60	21.7555	53.7590	0.03	3.11
	60-80	0.7252	1.7920	0.00	0.10
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	19	7035.5700	17385.2452	10.40	
LANDUSE:					
	Water --> WATR	2.9914	7.3919	0.00	0.04
	Wetlands-Mixed --> WETL	83.3962	206.0762	0.12	1.19
	Mixed forest --> FRST	312.6451	772.5617	0.46	4.44
	Pasture --> PAST	4547.0871	11236.0796	6.72	64.63
	Barren land --> BARR	38.1628	94.3023	0.06	0.54
	Urban --> URBN	1808.7910	4469.6131	2.67	25.71
SOILS:					
	I-Bc-L-2--640	6793.0737	16786.0247	10.04	96.55
SLOPE:					
	0-20	3302.3082	8160.1686	4.88	46.94
	20-40	2002.1433	4947.3962	2.96	28.46
	40-60	881.7335	2178.8076	1.30	12.53
	60-80	353.7087	874.0318	0.52	5.03
	80-9999	253.1800	625.6204	0.37	3.60

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	20	4315.5000	10663.8163	6.38	
LANDUSE:					
	Water --> WATR	0.3626	0.8960	0.00	0.01
	Wetlands-Mixed --> WETL	16.6792	41.2152	0.02	0.39
	Mixed forest --> FRST	178.4860	441.0478	0.26	4.14
	Pasture --> PAST	2970.6270	7340.5678	4.39	68.84
	Agricultural Land-Generic --> AGR	189.3638	467.9273	0.28	4.39
	Barren land --> BARR	18.2203	45.0232	0.03	0.42
	Urban --> URB	972.8348	2403.9234	1.44	22.54
SOILS:					
	I-Bc-L-2--640	4346.5736	10740.6008	6.42	100.72
SLOPE:					
	0-20	2607.8535	6444.1365	3.85	60.43
	20-40	1419.0045	3506.4310	2.10	32.88
	40-60	266.0520	657.4278	0.39	6.17
	60-80	46.3211	114.4619	0.07	1.07
	80-9999	7.3425	18.1437	0.01	0.17
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	21	1277.3700	3156.4451	1.89	
LANDUSE:					
	Wetlands-Mixed --> WETL	28.0102	69.2147	0.04	2.19
	Mixed forest --> FRST	81.8552	202.2682	0.12	6.41
	Pasture --> PAST	900.0444	2224.0547	1.33	70.46
	Agricultural Land-Generic --> AGR	5.9828	14.7837	0.01	0.47
	Barren land --> BARR	10.6058	26.2075	0.02	0.83
	Urban --> URB	260.0692	642.6441	0.38	20.36
SOILS:					
	I-Bc-L-2--640	1286.5677	3179.1730	1.90	100.72
SLOPE:					
	0-20	685.6618	1694.3046	1.01	53.68
	20-40	463.7554	1145.9627	0.69	36.31
	40-60	103.5201	255.8033	0.15	8.10
	60-80	22.7527	56.2230	0.03	1.78
	80-9999	10.8778	26.8795	0.02	0.85

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	22	3689.9100	9117.9521	5.45	
LANDUSE:					
	Water --> WATR	6.6173	16.3517	0.01	0.18
	Wetlands-Mixed --> WETL	20.2145	49.9511	0.03	0.55
	Mixed forest --> FRST	211.3912	522.3583	0.31	5.73
	Pasture --> PAST	2597.6103	6418.8249	3.84	70.40
	Barren land --> BARR	4.8043	11.8718	0.01	0.13
	Urban --> URBN	875.8414	2164.2479	1.29	23.74
SOILS:					
	I-Bc-L-2--640	3716.4791	9183.6057	5.49	100.72
SLOPE:					
	0-20	1417.0102	3501.5031	2.09	38.40
	20-40	1106.6313	2734.5413	1.64	29.99
	40-60	738.8722	1825.7901	1.09	20.02
	60-80	303.1271	749.0421	0.45	8.22
	80-9999	150.8383	372.7291	0.22	4.09
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	23	2670.9300	6600.0016	3.95	
LANDUSE:					
	Wetlands-Mixed --> WETL	21.0303	51.9670	0.03	0.79
	Mixed forest --> FRST	206.8588	511.1585	0.31	7.74
	Pasture --> PAST	2398.6379	5927.1541	3.55	89.81
	Barren land --> BARR	2.3568	5.8239	0.00	0.09
	Urban --> URBN	60.0997	148.5092	0.09	2.25
SOILS:					
	I-Bc-L-2--640	2688.9835	6644.6128	3.97	100.68
SLOPE:					
	0-20	581.0540	1435.8134	0.86	21.75
	20-40	972.7441	2403.6994	1.44	36.42
	40-60	740.6852	1830.2701	1.09	27.73
	60-80	268.3182	663.0277	0.40	10.05
	80-9999	126.1821	311.8022	0.19	4.72

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	24	2794.5000	6905.3492	4.13	
LANDUSE:					
	Wetlands-Mixed --> WETL	7.9770	19.7116	0.01	0.29
	Mixed forest --> FRST	178.8486	441.9438	0.26	6.40
	Pasture --> PAST	2501.5234	6181.3893	3.70	89.52
	Barren land --> BARR	3.3540	8.2878	0.00	0.12
	Urban --> URBN	118.3863	292.5386	0.17	4.24
SOILS:					
	I-Bc-L-2--640	2810.0893	6943.8712	4.15	100.56
SLOPE:					
	0-20	682.1265	1685.5687	1.01	24.41
	20-40	869.7680	2149.2401	1.29	31.12
	40-60	777.8509	1922.1083	1.15	27.84
	60-80	347.9978	859.9201	0.51	12.45
	80-9999	132.3461	327.0339	0.20	4.74
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	25	6121.9800	15127.7187	9.05	
LANDUSE:					
	Water --> WATR	96.7215	239.0036	0.14	1.58
	Wetlands-Mixed --> WETL	7.1612	17.6957	0.01	0.12
	Mixed forest --> FRST	452.8776	1119.0832	0.67	7.40
	Pasture --> PAST	5154.2477	12736.4038	7.62	84.19
	Barren land --> BARR	141.2297	348.9855	0.21	2.31
	Urban --> URBN	246.3814	608.8207	0.36	4.02
SOILS:					
	I-Bc-L-2--640	6098.6190	15069.9925	9.01	99.62
SLOPE:					
	0-20	1372.6833	3391.9691	2.03	22.42
	20-40	1831.6343	4526.0600	2.71	29.92
	40-60	1476.5660	3648.6683	2.18	24.12
	60-80	844.9304	2087.8653	1.25	13.80
	80-9999	572.8050	1415.4297	0.85	9.36

Appendix B: Study area topographic report generated by ArcSWAT using LULC 2018

Watershed		Area [ha]	Area[acres]		
Number of Subbasins: 25		67654.2600	167177.0592		
		Area [ha]	Area[acres]	%Wat.Area	
LANDUSE:					
	Water --> WATR	191.9926	474.4232	0.28	
	Wetlands-Mixed --> WETL	753.8291	1862.7494	1.11	
	Mixed forest --> FRST	1450.9126	3585.2775	2.14	
	Pasture --> PAST	43858.9676	108377.7018	64.83	
	Agricultural Land-Generic --> AGR1	5424.6508	13404.5834	8.02	
	Barren land --> BARR	3145.1245	7771.7598	4.65	
	Urban --> URB1	12828.7829	31700.5640	18.96	
SOILS:					
	Fr20-3bc-575	83.2149	205.6282	0.12	
	I-Bc-L-2--640	51897.5453	128241.4294	76.71	
	Ws13-2ab-985	15673.4998	38730.0016	23.17	
SLOPE:					
	0-20	39479.7606	97556.4625	58.36	
	20-40	16985.3582	41971.6695	25.11	
	40-60	7097.2885	17537.7547	10.49	
	60-80	2642.2998	6529.2549	3.91	
	80-9999	1449.5528	3581.9176	2.14	
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	1	756.8100	1870.1154	1.12	
LANDUSE:					
	Water --> WATR	0.6345	1.5680	0.00	0.08
	Wetlands-Mixed --> WETL	16.7699	41.4392	0.02	2.22
	Mixed forest --> FRST	5.3482	13.2158	0.01	0.71
	Pasture --> PAST	397.7636	982.8938	0.59	52.56
	Agricultural Land-Generic --> AGR1	335.0352	827.8886	0.50	44.27
	Barren land --> BARR	4.1698	10.3038	0.01	0.55
	Urban --> URB1	2.5381	6.2719	0.00	0.34
SOILS:					
	Ws13-2ab-985	762.2594	1883.5811	1.13	100.72
SLOPE:					
	0-20	759.0867	1875.7412	1.12	100.30
	20-40	3.1727	7.8399	0.00	0.42

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	2	1609.5600	3977.3032	2.38	
LANDUSE:					
	Water --> WATR	5.4389	13.4398	0.01	0.34
	Wetlands-Mixed --> WETL	2.9914	7.3919	0.00	0.19
	Mixed forest --> FRST	4.8043	11.8718	0.01	0.30
	Pasture --> PAST	1197.6419	2959.4331	1.77	74.41
	Agricultural Land-Generic --> AGRL	282.1874	697.2991	0.42	17.53
	Barren land --> BARR	89.2883	220.6359	0.13	5.55
	Urban --> URBN	38.7974	95.8702	0.06	2.41
SOILS:					
	Ws13-2ab-985	1621.1496	4005.9417	2.40	100.72
SLOPE:					
	0-20	1477.9257	3652.0283	2.18	91.82
	20-40	129.4454	319.8661	0.19	8.04
	40-60	13.5066	33.3754	0.02	0.84
	60-80	0.2719	0.6720	0.00	0.02
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	3	3414.3300	8436.9801	5.05	
LANDUSE:					
	Water --> WATR	0.9065	2.2400	0.00	0.03
	Wetlands-Mixed --> WETL	105.4237	260.5072	0.16	3.09
	Mixed forest --> FRST	2.1756	5.3759	0.00	0.06
	Pasture --> PAST	2447.4065	6047.6638	3.62	71.68
	Agricultural Land-Generic --> AGRL	831.0613	2053.5939	1.23	24.34
	Barren land --> BARR	40.1571	99.2302	0.06	1.18
	Urban --> URBN	11.7842	29.1195	0.02	0.35
SOILS:					
	I-Bc-L-2--640	2256.5017	5575.9286	3.34	66.09
	Ws13-2ab-985	1182.4131	2921.8018	1.75	34.63
SLOPE:					
	0-20	3221.0875	7959.4684	4.76	94.34
	20-40	202.1451	499.5107	0.30	5.92
	40-60	15.0476	37.1833	0.02	0.44
	60-80	0.6345	1.5680	0.00	0.02

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	4	1831.9500	4526.8400	2.71	
LANDUSE:					
	Water --> WATR	0.0906	0.2240	0.00	0.00
	Wetlands-Mixed --> WETL	65.7198	162.3970	0.10	3.59
	Mixed forest --> FRST	5.8921	14.5597	0.01	0.32
	Pasture --> PAST	913.1884	2256.5341	1.35	49.85
	Agricultural Land-Generic --> AGR	468.4691	1157.6105	0.69	25.57
	Barren land --> BARR	71.7932	177.4047	0.11	3.92
	Urban --> URB	319.9876	790.7053	0.47	17.47
SOILS:					
	I-Bc-L-2--640	1298.6239	3208.9645	1.92	70.89
	Ws13-2ab-985	546.5170	1350.4710	0.81	29.83
SLOPE:					
	0-20	1663.4822	4110.5478	2.46	90.80
	20-40	159.3593	393.7847	0.24	8.70
	40-60	20.0332	49.5031	0.03	1.09
	60-80	2.2662	5.5999	0.00	0.12
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	5	2437.7400	6023.7774	3.60	
LANDUSE:					
	Water --> WATR	0.6345	1.5680	0.00	0.03
	Wetlands-Mixed --> WETL	54.6608	135.0695	0.08	2.24
	Mixed forest --> FRST	83.1243	205.4042	0.12	3.41
	Pasture --> PAST	1801.0860	4450.5735	2.66	73.88
	Agricultural Land-Generic --> AGR	209.6689	518.1024	0.31	8.60
	Barren land --> BARR	267.5930	661.2357	0.40	10.98
	Urban --> URB	38.5254	95.1982	0.06	1.58
SOILS:					
	I-Bc-L-2--640	2455.2929	6067.1515	3.63	100.72
SLOPE:					
	0-20	1956.7286	4835.1743	2.89	80.27
	20-40	387.7017	958.0302	0.57	15.90
	40-60	63.2723	156.3491	0.09	2.60
	60-80	19.0361	47.0391	0.03	0.78
	80-9999	28.5541	70.5587	0.04	1.17

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	6	3648.9600	9016.7626	5.39	
LANDUSE:					
	Water --> WATR	0.1813	0.4480	0.00	0.00
	Wetlands-Mixed --> WETL	20.1239	49.7271	0.03	0.55
	Mixed forest --> FRST	11.1497	27.5515	0.02	0.31
	Pasture --> PAST	2865.5659	7080.9567	4.24	78.53
	Agricultural Land-Generic --> AGRL	442.4531	1093.3237	0.65	12.13
	Barren land --> BARR	202.1451	499.5107	0.30	5.54
	Urban --> URBN	133.6152	330.1699	0.20	3.66
SOILS:					
	I-Bc-L-2--640	350.5360	866.1919	0.52	9.61
	Ws13-2ab-985	3324.6983	8215.4956	4.91	91.11
SLOPE:					
	0-20	2910.9806	7193.1786	4.30	79.78
	20-40	623.8398	1541.5394	0.92	17.10
	40-60	123.4626	305.0823	0.18	3.38
	60-80	13.3253	32.9274	0.02	0.37
	80-9999	3.6259	8.9598	0.01	0.10

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	7	1424.7000	3520.5049	2.11	
LANDUSE:					
	Water --> WATR	0.6345	1.5680	0.00	0.04
	Wetlands-Mixed --> WETL	57.0176	140.8934	0.08	4.00
	Mixed forest --> FRST	10.9684	27.1035	0.02	0.77
	Pasture --> PAST	439.6430	1086.3798	0.65	30.86
	Agricultural Land-Generic --> AGRL	175.2227	432.9840	0.26	12.30
	Barren land --> BARR	102.7042	253.7873	0.15	7.21
	Urban --> URBN	648.7680	1603.1383	0.96	45.54
SOILS:					
	I-Bc-L-2--640	1140.4430	2818.0917	1.69	80.05
	Ws13-2ab-985	294.5155	727.7625	0.44	20.67
SLOPE:					
	0-20	1224.7457	3026.4079	1.81	85.97
	20-40	189.4544	468.1513	0.28	13.30
	40-60	20.5771	50.8471	0.03	1.44
	60-80	0.1813	0.4480	0.00	0.01

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	8	2234.6100	5521.8330	3.30	
LANDUSE:					
	Water --> WATR	1.4504	3.5839	0.00	0.06
	Mixed forest --> FRST	10.7871	26.6555	0.02	0.48
	Pasture --> PAST	1952.9214	4825.7665	2.89	87.39
	Agricultural Land-Generic --> AGRL	147.3937	364.2172	0.22	6.60
	Barren land --> BARR	119.3835	295.0025	0.18	5.34
	Urban --> URBN	18.7641	46.3671	0.03	0.84
SOILS:					
	Fr20-3bc-575	59.9184	148.0613	0.09	2.68
	I-Bc-L-2--640	1.5410	3.8079	0.00	0.07
	Ws13-2ab-985	2189.2409	5409.7237	3.24	97.97
SLOPE:					
	0-20	1289.5591	3186.5649	1.91	57.71
	20-40	729.5354	1802.7186	1.08	32.65
	40-60	182.2932	450.4556	0.27	8.16
	60-80	40.6103	100.3501	0.06	1.82
	80-9999	8.7022	21.5036	0.01	0.39
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	9	2182.6800	5393.5114	3.23	
LANDUSE:					
	Water --> WATR	0.1813	0.4480	0.00	0.01
	Wetlands-Mixed --> WETL	5.4389	13.4398	0.01	0.25
	Mixed forest --> FRST	27.0131	66.7508	0.04	1.24
	Pasture --> PAST	1666.4736	4117.9396	2.46	76.35
	Agricultural Land-Generic --> AGRL	233.6000	577.2373	0.35	10.70
	Barren land --> BARR	255.8994	632.3403	0.38	11.72
	Urban --> URBN	9.7900	24.1916	0.01	0.45
SOILS:					
	Ws13-2ab-985	2198.3963	5432.3472	3.25	100.72
SLOPE:					
	0-20	1247.0451	3081.5108	1.84	57.13
	20-40	718.1138	1774.4951	1.06	32.90
	40-60	189.4544	468.1513	0.28	8.68
	60-80	36.4405	90.0463	0.05	1.67
	80-9999	7.3425	18.1437	0.01	0.34

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	10	256.5000	633.8243	0.38	
LANDUSE:					
	Water --> WATR	1.2691	3.1359	0.00	0.49
	Wetlands-Mixed --> WETL	8.7929	21.7276	0.01	3.43
	Mixed forest --> FRST	2.8101	6.9439	0.00	1.10
	Pasture --> PAST	27.1038	66.9748	0.04	10.57
	Agricultural Land-Generic --> AGRL	67.7141	167.3249	0.10	26.40
	Barren land --> BARR	2.5381	6.2719	0.00	0.99
	Urban --> URBN	148.1189	366.0092	0.22	57.75
SOILS:					
	I-Bc-L-2--640	258.3469	638.3882	0.38	100.72
SLOPE:					
	0-20	250.6418	619.3485	0.37	97.72
	20-40	7.6144	18.8157	0.01	2.97
	40-60	0.0906	0.2240	0.00	0.04
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	11	360.8100	891.5796	0.53	
LANDUSE:					
	Water --> WATR	0.0906	0.2240	0.00	0.03
	Wetlands-Mixed --> WETL	15.1382	37.4073	0.02	4.20
	Mixed forest --> FRST	2.9914	7.3919	0.00	0.83
	Pasture --> PAST	49.4032	122.0777	0.07	13.69
	Agricultural Land-Generic --> AGRL	56.2924	139.1014	0.08	15.60
	Barren land --> BARR	3.8979	9.6318	0.01	1.08
	Urban --> URBN	235.5943	582.1652	0.35	65.30
SOILS:					
	I-Bc-L-2--640	363.4080	897.9993	0.54	100.72
SLOPE:					
	0-20	358.6037	886.1276	0.53	99.39
	20-40	4.8043	11.8718	0.01	1.33

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	12	1726.0200	4265.0817	2.55	
LANDUSE:					
	Wetlands-Mixed --> WETL	42.5139	105.0541	0.06	2.46
	Mixed forest --> FRST	14.8663	36.7353	0.02	0.86
	Pasture --> PAST	420.5163	1039.1167	0.62	24.36
	Agricultural Land-Generic --> AGR	69.8896	172.7008	0.10	4.05
	Barren land --> BARR	43.5111	107.5180	0.06	2.52
	Urban --> URB	1147.1510	2834.6674	1.70	66.46
SOILS:					
	I-Bc-L-2--640	1738.4482	4295.7923	2.57	100.72
SLOPE:					
	0-20	1320.5607	3263.1715	1.95	76.51
	20-40	351.9863	869.7759	0.52	20.39
	40-60	48.8593	120.7338	0.07	2.83
	60-80	8.7022	21.5036	0.01	0.50
	80-9999	8.3396	20.6076	0.01	0.48
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	13	7559.8200	18680.6932	11.17	
LANDUSE:					
	Water --> WATR	3.0820	7.6159	0.00	0.04
	Wetlands-Mixed --> WETL	178.5766	441.2718	0.26	2.36
	Mixed forest --> FRST	383.6225	947.9504	0.57	5.07
	Pasture --> PAST	3687.8343	9112.8230	5.45	48.78
	Agricultural Land-Generic --> AGR	489.2275	1208.9056	0.72	6.47
	Barren land --> BARR	412.2673	1018.7331	0.61	5.45
	Urban --> URB	2429.7301	6003.9846	3.59	32.14
SOILS:					
	I-Bc-L-2--640	7584.3404	18741.2844	11.21	100.32
SLOPE:					
	0-20	4340.9535	10726.7130	6.42	57.42
	20-40	2209.0021	5458.5548	3.27	29.22
	40-60	735.3369	1817.0543	1.09	9.73
	60-80	190.7235	471.2873	0.28	2.52
	80-9999	108.3244	267.6750	0.16	1.43

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	14	3337.6500	8247.5000	4.93	
LANDUSE:					
	Water --> WATR	3.4446	8.5118	0.01	0.10
	Wetlands-Mixed --> WETL	39.2506	96.9902	0.06	1.18
	Mixed forest --> FRST	16.4979	40.7672	0.02	0.49
	Pasture --> PAST	748.2089	1848.8617	1.11	22.42
	Agricultural Land-Generic --> AGRL	106.6021	263.4191	0.16	3.19
	Barren land --> BARR	129.5361	320.0901	0.19	3.88
	Urban --> URBN	2318.1424	5728.2458	3.43	69.45
SOILS:					
	I-Bc-L-2--640	1688.9543	4173.4906	2.50	50.60
	Ws13-2ab-985	1672.7283	4133.3953	2.47	50.12
SLOPE:					
	0-20	2683.9979	6632.2930	3.97	80.42
	20-40	504.4564	1246.5369	0.75	15.11
	40-60	137.3318	339.3537	0.20	4.11
	60-80	26.3786	65.1828	0.04	0.79
	80-9999	9.5180	23.5196	0.01	0.29
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	15	389.2500	961.8562	0.58	
LANDUSE:					
	Water --> WATR	1.1784	2.9119	0.00	0.30
	Wetlands-Mixed --> WETL	0.9971	2.4640	0.00	0.26
	Mixed forest --> FRST	1.1784	2.9119	0.00	0.30
	Pasture --> PAST	44.8708	110.8779	0.07	11.53
	Agricultural Land-Generic --> AGRL	123.6439	305.5303	0.18	31.76
	Barren land --> BARR	20.5771	50.8471	0.03	5.29
	Urban --> URBN	199.6070	493.2389	0.30	51.28
SOILS:					
	I-Bc-L-2--640	392.0528	968.7820	0.58	100.72
SLOPE:					
	0-20	312.9170	773.2337	0.46	80.39
	20-40	69.8896	172.7008	0.10	17.95
	40-60	8.0677	19.9356	0.01	2.07
	60-80	1.1784	2.9119	0.00	0.30

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	16	5554.7100	13725.9661	8.21	
LANDUSE:					
	Water --> WATR	60.8248	150.3012	0.09	1.10
	Wetlands-Mixed --> WETL	4.9856	12.3198	0.01	0.09
	Mixed forest --> FRST	106.4208	262.9711	0.16	1.92
	Pasture --> PAST	4423.0806	10929.6533	6.54	79.63
	Agricultural Land-Generic --> AGRL	206.7682	510.9345	0.31	3.72
	Barren land --> BARR	302.6738	747.9221	0.45	5.45
	Urban --> URBN	399.0327	986.0297	0.59	7.18
SOILS:					
	Fr20-3bc-575	23.2965	57.5669	0.03	0.42
	I-Bc-L-2--640	3598.9086	8893.0830	5.32	64.79
	Ws13-2ab-985	1881.5814	4649.4818	2.78	33.87
SLOPE:					
	0-20	3076.8665	7603.0910	4.55	55.39
	20-40	1766.6397	4365.4550	2.61	31.80
	40-60	524.1270	1295.1440	0.77	9.44
	60-80	114.5791	283.1307	0.17	2.06
	80-9999	21.5742	53.3110	0.03	0.39
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	17	323.9100	800.3978	0.48	
LANDUSE:					
	Water --> WATR	0.0906	0.2240	0.00	0.03
	Wetlands-Mixed --> WETL	0.5439	1.3440	0.00	0.17
	Mixed forest --> FRST	5.7108	14.1117	0.01	1.76
	Pasture --> PAST	147.3031	363.9932	0.22	45.48
	Agricultural Land-Generic --> AGRL	56.0205	138.4294	0.08	17.30
	Barren land --> BARR	18.4016	45.4712	0.03	5.68
	Urban --> URBN	98.1718	242.5875	0.15	30.31
SOILS:					
	I-Bc-L-2--640	326.2423	806.1610	0.48	100.72
SLOPE:					
	0-20	246.0188	607.9247	0.36	75.95
	20-40	71.3400	176.2847	0.11	22.02
	40-60	8.7929	21.7276	0.01	2.71
	60-80	0.0906	0.2240	0.00	0.03

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	18	698.4900	1726.0037	1.03	
LANDUSE:					
	Water --> WATR	0.3626	0.8960	0.00	0.05
	Mixed forest --> FRST	66.8983	165.3089	0.10	9.58
	Pasture --> PAST	242.6648	599.6369	0.36	34.74
	Agricultural Land-Generic --> AGR	112.8568	278.8748	0.17	16.16
	Barren land --> BARR	26.5599	65.6308	0.04	3.80
	Urban --> URB	254.1771	628.0844	0.38	36.39
SOILS:					
	I-Bc-L-2--640	703.5195	1738.4318	1.04	100.72
SLOPE:					
	0-20	489.8620	1210.4735	0.72	70.13
	20-40	191.1767	472.4072	0.28	27.37
	40-60	21.7555	53.7590	0.03	3.11
	60-80	0.7252	1.7920	0.00	0.10
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	19	7035.5700	17385.2452	10.40	
LANDUSE:					
	Water --> WATR	2.7194	6.7199	0.00	0.04
	Wetlands-Mixed --> WETL	76.1444	188.1565	0.11	1.08
	Mixed forest --> FRST	85.3905	211.0041	0.13	1.21
	Pasture --> PAST	4408.4862	10893.5899	6.52	62.66
	Agricultural Land-Generic --> AGR	40.6103	100.3501	0.06	0.58
	Barren land --> BARR	367.6685	908.5271	0.54	5.23
	Urban --> URB	1812.0544	4477.6769	2.68	25.76
SOILS:					
	I-Bc-L-2--640	6793.0737	16786.0247	10.04	96.55
SLOPE:					
	0-20	3302.3082	8160.1686	4.88	46.94
	20-40	2002.1433	4947.3962	2.96	28.46
	40-60	881.7335	2178.8076	1.30	12.53
	60-80	353.7087	874.0318	0.52	5.03
	80-9999	253.1800	625.6204	0.37	3.60

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	20	4315.5000	10663.8163	6.38	
LANDUSE:					
	Water --> WATR	0.3626	0.8960	0.00	0.01
	Wetlands-Mixed --> WETL	7.8864	19.4876	0.01	0.18
	Mixed forest --> FRST	138.7822	342.9376	0.21	3.22
	Pasture --> PAST	2520.0156	6227.0845	3.72	58.39
	Agricultural Land-Generic --> AGRL	524.1270	1295.1440	0.77	12.15
	Barren land --> BARR	167.6989	414.3923	0.25	3.89
	Urban --> URBN	987.7011	2440.6587	1.46	22.89
SOILS:					
	I-Bc-L-2--640	4346.5736	10740.6008	6.42	100.72
SLOPE:					
	0-20	2607.8535	6444.1365	3.85	60.43
	20-40	1419.0045	3506.4310	2.10	32.88
	40-60	266.0520	657.4278	0.39	6.17
	60-80	46.3211	114.4619	0.07	1.07
	80-9999	7.3425	18.1437	0.01	0.17
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	21	1277.3700	3156.4451	1.89	
LANDUSE:					
	Water --> WATR	0.0906	0.2240	0.00	0.01
	Wetlands-Mixed --> WETL	11.8749	29.3435	0.02	0.93
	Mixed forest --> FRST	44.8708	110.8779	0.07	3.51
	Pasture --> PAST	816.7389	2018.2026	1.21	63.94
	Agricultural Land-Generic --> AGRL	115.5763	285.5947	0.17	9.05
	Barren land --> BARR	43.8737	108.4140	0.06	3.43
	Urban --> URBN	253.5426	626.5164	0.37	19.85
SOILS:					
	I-Bc-L-2--640	1286.5677	3179.1730	1.90	100.72
SLOPE:					
	0-20	685.6618	1694.3046	1.01	53.68
	20-40	463.7554	1145.9627	0.69	36.31
	40-60	103.5201	255.8033	0.15	8.10
	60-80	22.7527	56.2230	0.03	1.78
	80-9999	10.8778	26.8795	0.02	0.85

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	22	3689.9100	9117.9521	5.45	
LANDUSE:					
	Water --> WATR	4.7137	11.6478	0.01	0.13
	Wetlands-Mixed --> WETL	15.8634	39.1993	0.02	0.43
	Mixed forest --> FRST	109.5028	270.5870	0.16	2.97
	Pasture --> PAST	2519.1997	6225.0685	3.72	68.27
	Agricultural Land-Generic --> AGRL	70.1616	173.3728	0.10	1.90
	Barren land --> BARR	95.0898	234.9716	0.14	2.58
	Urban --> URBN	901.9480	2228.7587	1.33	24.44
SOILS:					
	I-Bc-L-2--640	3716.4791	9183.6057	5.49	100.72
SLOPE:					
	0-20	1417.0102	3501.5031	2.09	38.40
	20-40	1106.6313	2734.5413	1.64	29.99
	40-60	738.8722	1825.7901	1.09	20.02
	60-80	303.1271	749.0421	0.45	8.22
	80-9999	150.8383	372.7291	0.22	4.09

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	23	2670.9300	6600.0016	3.95	
LANDUSE:					
	Water --> WATR	0.0906	0.2240	0.00	0.00
	Wetlands-Mixed --> WETL	17.4951	43.2312	0.03	0.66
	Mixed forest --> FRST	138.2383	341.5937	0.20	5.18
	Pasture --> PAST	2274.2687	5619.8318	3.36	85.15
	Agricultural Land-Generic --> AGRL	69.7990	172.4768	0.10	2.61
	Barren land --> BARR	124.1878	306.8743	0.18	4.65
	Urban --> URBN	64.9040	160.3810	0.10	2.43
SOILS:					
	I-Bc-L-2--640	2688.9835	6644.6128	3.97	100.68
SLOPE:					
	0-20	581.0540	1435.8134	0.86	21.75
	20-40	972.7441	2403.6994	1.44	36.42
	40-60	740.6852	1830.2701	1.09	27.73
	60-80	268.3182	663.0277	0.40	10.05
	80-9999	126.1821	311.8022	0.19	4.72

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	24	2794.5000	6905.3492	4.13	
LANDUSE:					
	Wetlands-Mixed --> WETL	1.4504	3.5839	0.00	0.05
	Mixed forest --> FRST	107.2366	264.9871	0.16	3.84
	Pasture --> PAST	2357.3023	5825.0120	3.48	84.36
	Agricultural Land-Generic --> AGRL	121.2871	299.7064	0.18	4.34
	Barren land --> BARR	99.4409	245.7234	0.15	3.56
	Urban --> URBN	123.3720	304.8583	0.18	4.41
SOILS:					
	I-Bc-L-2--640	2810.0893	6943.8712	4.15	100.56
SLOPE:					
	0-20	682.1265	1685.5687	1.01	24.41
	20-40	869.7680	2149.2401	1.29	31.12
	40-60	777.8509	1922.1083	1.15	27.84
	60-80	347.9978	859.9201	0.51	12.45
	80-9999	132.3461	327.0339	0.20	4.74
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	25	6121.9800	15127.7187	9.05	
LANDUSE:					
	Water --> WATR	103.5201	255.8033	0.15	1.69
	Wetlands-Mixed --> WETL	4.1698	10.3038	0.01	0.07
	Mixed forest --> FRST	64.6321	159.7090	0.10	1.06
	Pasture --> PAST	5490.2800	13566.7564	8.12	89.68
	Agricultural Land-Generic --> AGRL	68.9832	170.4608	0.10	1.13
	Barren land --> BARR	134.0685	331.2899	0.20	2.19
	Urban --> URBN	232.9655	575.6693	0.34	3.81
SOILS:					
	I-Bc-L-2--640	6098.6190	15069.9925	9.01	99.62
SLOPE:					
	0-20	1372.6833	3391.9691	2.03	22.42
	20-40	1831.6343	4526.0600	2.71	29.92
	40-60	1476.5660	3648.6683	2.18	24.12
	60-80	844.9304	2087.8653	1.25	13.80
	80-9999	572.8050	1415.4297	0.85	9.36

Appendix C: Final HRU land use, soil, and slope report (1990 LULC)

MULTIPLE HRUs LandUse/Soil/Slope OPTION

THRESHOLDS : 20 / 10 / 10 [%]

Number of HRUs: 90

Number of Subbasins: 25

		Area [ha]	Area[acres]		
Watershed		67654.2600	167177.0592		
		Area [ha]	Area[acres]	%Wat.Area	
LANDUSE:					
	Pasture --> PAST	55570.2247	137316.8037	82.14	
	Agricultural Land-Generic --> AGRL	756.9063	1870.3533	1.12	
	Urban --> URBN	11327.1291	27989.9023	16.74	
SOILS:					
	Ws13-2ab-985	16179.0921	39979.3455	23.91	
	I-Bc-L-2--640	51475.1679	127197.7137	76.09	
SLOPE:					
	0-20	41593.7441	102780.2214	61.48	
	20-40	17996.1287	44469.3339	26.60	
	40-60	6074.0969	15009.3971	8.98	
	60-80	1990.2902	4918.1067	2.94	
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area
SUBBASIN #	1	756.8100	1870.1154	1.12	
LANDUSE:					
	Pasture --> PAST	464.5179	1147.8470	0.69	61.38
	Agricultural Land-Generic --> AGRL	297.7415	735.7340	0.44	39.34
SOILS:					
	Ws13-2ab-985	762.2594	1883.5811	1.13	100.72
SLOPE:					
	0-20	762.2594	1883.5811	1.13	100.72
HRUs					
1	Pasture --> PAST/Ws13-2ab-985/0-20	464.5179	1147.8470	0.69	61.38 1
2	Agricultural Land-Generic --> AGRL/Ws13-2ab-985/0-20	297.7415	735.7340	0.44	39.34 2

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	2	1609.5600	3977.3032	2.38		
LANDUSE:						
	Pasture --> PAST	1621.1496	4005.9417	2.40	100.72	
SOILS:						
	Ws13-2ab-985	1621.1496	4005.9417	2.40	100.72	
SLOPE:						
	0-20	1621.1496	4005.9417	2.40	100.72	
HRUs						
3	Pasture --> PAST/Ws13-2ab-985/0-20	1621.1496	4005.9417	2.40	100.72	1
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	3	3414.3300	8436.9801	5.05		
LANDUSE:						
	Pasture --> PAST	3438.9148	8497.7304	5.08	100.72	
SOILS:						
	I-Bc-L-2--640	2122.8397	5245.6431	3.14	62.17	
	Ws13-2ab-985	1316.0750	3252.0872	1.95	38.55	
SLOPE:						
	0-20	3438.9148	8497.7304	5.08	100.72	
HRUs						
4	Pasture --> PAST/I-Bc-L-2--640/0-20	2122.8397	5245.6431	3.14	62.17	1
5	Pasture --> PAST/Ws13-2ab-985/0-20	1316.0750	3252.0872	1.95	38.55	2

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	4	1831.9500	4526.8400	2.71		
LANDUSE:						
	Pasture --> PAST	1385.9761	3424.8162	2.05	75.66	
	Agricultural Land-Generic --> AGRL	459.1648	1134.6192	0.68	25.06	
SOILS:						
	I-Bc-L-2--640	1296.6298	3204.0370	1.92	70.78	
	Ws13-2ab-985	548.5111	1355.3984	0.81	29.94	
SLOPE:						
	20-40	158.5165	391.7021	0.23	8.65	
	0-20	1686.6244	4167.7333	2.49	92.07	
HRUs						
6	Pasture --> PAST/I-Bc-L-2--640/20-40	85.2257	210.5970	0.13	4.65	1
7	Pasture --> PAST/I-Bc-L-2--640/0-20	752.2393	1858.8208	1.11	41.06	2
8	Pasture --> PAST/Ws13-2ab-985/20-40	73.2908	181.1051	0.11	4.00	3
9	Pasture --> PAST/Ws13-2ab-985/0-20	475.2204	1174.2933	0.70	25.94	4
10	Agricultural Land-Generic --> AGRL/I-Bc-L-2--640/0-20	459.1648	1134.6192	0.68	25.06	5
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	5	2437.7400	6023.7774	3.60		
LANDUSE:						
	Pasture --> PAST	2455.2929	6067.1515	3.63	100.72	
SOILS:						
	I-Bc-L-2--640	2455.2929	6067.1515	3.63	100.72	
SLOPE:						
	20-40	420.6088	1039.3453	0.62	17.25	
	0-20	2034.6841	5027.8061	3.01	83.47	
HRUs						
11	Pasture --> PAST/I-Bc-L-2--640/20-40	420.6088	1039.3453	0.62	17.25	1
12	Pasture --> PAST/I-Bc-L-2--640/0-20	2034.6841	5027.8061	3.01	83.47	2

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	6	3648.9600	9016.7626	5.39		
LANDUSE:						
	Pasture --> PAST	3675.2342	9081.6876	5.43	100.72	
SOILS:						
	Ws13-2ab-985	3675.2342	9081.6876	5.43	100.72	
SLOPE:						
	0-20	3023.9210	7472.2599	4.47	82.87	
	20-40	651.3133	1609.4276	0.96	17.85	
HRUs						
13	Pasture --> PAST/Ws13-2ab-985/0-20	3023.9210	7472.2599	4.47	82.87	1
14	Pasture --> PAST/Ws13-2ab-985/20-40	651.3133	1609.4276	0.96	17.85	2
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	7	1424.7000	3520.5049	2.11		
LANDUSE:						
	Pasture --> PAST	1434.9585	3545.8542	2.12	100.72	
SOILS:						
	I-Bc-L-2--640	1116.7261	2759.4860	1.65	78.38	
	Ws13-2ab-985	318.2324	786.3682	0.47	22.34	
SLOPE:						
	20-40	202.8893	501.3496	0.30	14.24	
	0-20	1232.0692	3044.5047	1.82	86.48	
HRUs						
15	Pasture --> PAST/I-Bc-L-2--640/20-40	167.1693	413.0837	0.25	11.73	1
16	Pasture --> PAST/I-Bc-L-2--640/0-20	949.5568	2346.4023	1.40	66.65	2
17	Pasture --> PAST/Ws13-2ab-985/0-20	282.5125	698.1024	0.42	19.83	3
18	Pasture --> PAST/Ws13-2ab-985/20-40	35.7200	88.2658	0.05	2.51	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	8	2234.6100	5521.8330	3.30		
LANDUSE:	Pasture --> PAST	2250.7002	5561.5928	3.33	100.72	
SOILS:	Ws13-2ab-985	2250.7002	5561.5928	3.33	100.72	
SLOPE:	0-20	1432.3983	3539.5279	2.12	64.10	
	20-40	818.3019	2022.0650	1.21	36.62	
HRUs						
19	Pasture --> PAST/Ws13-2ab-985/0-20	1432.3983	3539.5279	2.12	64.10	1
20	Pasture --> PAST/Ws13-2ab-985/20-40	818.3019	2022.0650	1.21	36.62	2
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	9	2182.6800	5393.5114	3.23		
LANDUSE:	Pasture --> PAST	2198.3963	5432.3472	3.25	100.72	
SOILS:	Ws13-2ab-985	2198.3963	5432.3472	3.25	100.72	
SLOPE:	0-20	1345.5692	3324.9687	1.99	61.65	
	20-40	852.8272	2107.3786	1.26	39.07	
HRUs						
21	Pasture --> PAST/Ws13-2ab-985/0-20	1345.5692	3324.9687	1.99	61.65	1
22	Pasture --> PAST/Ws13-2ab-985/20-40	852.8272	2107.3786	1.26	39.07	2
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	10	256.5000	633.8243	0.38		
LANDUSE:	Pasture --> PAST	99.2896	245.3497	0.15	38.71	
	Urban --> URBN	159.0573	393.0385	0.24	62.01	
SOILS:	I-Bc-L-2--640	258.3469	638.3882	0.38	100.72	
SLOPE:	0-20	258.3469	638.3882	0.38	100.72	
HRUs						
23	Pasture --> PAST/I-Bc-L-2--640/0-20	99.2896	245.3497	0.15	38.71	1
24	Urban --> URBN/I-Bc-L-2--640/0-20	159.0573	393.0385	0.24	62.01	2

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	11	360.8100	891.5796	0.53		
LANDUSE:						
	Pasture --> PAST	106.2961	262.6629	0.16	29.46	
	Urban --> URBN	257.1119	635.3364	0.38	71.26	
SOILS:						
	I-Bc-L-2--640	363.4080	897.9993	0.54	100.72	
SLOPE:						
	0-20	363.4080	897.9993	0.54	100.72	
HRUs						
25	Pasture --> PAST/I-Bc-L-2--640/0-20	106.2961	262.6629	0.16	29.46	1
26	Urban --> URBN/I-Bc-L-2--640/0-20	257.1119	635.3364	0.38	71.26	2
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	12	1726.0200	4265.0817	2.55		
LANDUSE:						
	Pasture --> PAST	473.1781	1169.2466	0.70	27.41	
	Urban --> URBN	1265.2701	3126.5457	1.87	73.31	
SOILS:						
	I-Bc-L-2--640	1738.4482	4295.7923	2.57	100.72	
SLOPE:						
	0-20	1363.0590	3368.1871	2.01	78.97	
	20-40	375.3891	927.6053	0.55	21.75	
HRUs						
27	Pasture --> PAST/I-Bc-L-2--640/0-20	247.5462	611.6989	0.37	14.34	1
28	Pasture --> PAST/I-Bc-L-2--640/20-40	225.6319	557.5477	0.33	13.07	2
29	Urban --> URBN/I-Bc-L-2--640/20-40	149.7572	370.0576	0.22	8.68	3
30	Urban --> URBN/I-Bc-L-2--640/0-20	1115.5129	2756.4881	1.65	64.63	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	13	7559.8200	18680.6932	11.17		
LANDUSE:						
	Pasture --> PAST	4758.7958	11759.2223	7.03	62.95	
	Urban --> URBN	2825.5446	6982.0621	4.18	37.38	
SOILS:						
	I-Bc-L-2--640	7584.3404	18741.2844	11.21	100.32	
SLOPE:						
	0-20	4459.6862	11020.1075	6.59	58.99	
	40-60	739.7760	1828.0236	1.09	9.79	
	20-40	2384.8782	5893.1533	3.53	31.55	
HRUs						
31	Pasture --> PAST/I-Bc-L-2--640/0-20	2147.6029	5306.8340	3.17	28.41	1
32	Pasture --> PAST/I-Bc-L-2--640/40-60	739.7760	1828.0236	1.09	9.79	2
33	Pasture --> PAST/I-Bc-L-2--640/20-40	1871.4169	4624.3647	2.77	24.75	3
34	Urban --> URBN/I-Bc-L-2--640/0-20	2312.0833	5713.2735	3.42	30.58	4
35	Urban --> URBN/I-Bc-L-2--640/20-40	513.4613	1268.7886	0.76	6.79	5
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	14	3337.6500	8247.5000	4.93		
LANDUSE:						
	Pasture --> PAST	1194.7770	2952.3538	1.77	35.80	
	Urban --> URBN	2166.9056	5354.5321	3.20	64.92	
SOILS:						
	I-Bc-L-2--640	1687.8535	4170.7704	2.49	50.57	
	Ws13-2ab-985	1673.8292	4136.1155	2.47	50.15	
SLOPE:						
	20-40	309.2979	764.2906	0.46	9.27	
	0-20	2975.8833	7353.5563	4.40	89.16	
	40-60	76.5015	189.0390	0.11	2.29	
HRUs						
36	Pasture --> PAST/I-Bc-L-2--640/20-40	147.1469	363.6074	0.22	4.41	1
37	Pasture --> PAST/I-Bc-L-2--640/0-20	503.7759	1244.8554	0.74	15.09	2
38	Pasture --> PAST/Ws13-2ab-985/40-60	76.5015	189.0390	0.11	2.29	3
39	Pasture --> PAST/Ws13-2ab-985/20-40	162.1510	400.6832	0.24	4.86	4
40	Pasture --> PAST/Ws13-2ab-985/0-20	305.2017	754.1688	0.45	9.14	5
41	Urban --> URBN/I-Bc-L-2--640/0-20	1036.9307	2562.3076	1.53	31.07	6
42	Urban --> URBN/Ws13-2ab-985/0-20	1129.9749	2792.2245	1.67	33.86	7

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	15	389.2500	961.8562	0.58		
LANDUSE:						
	Pasture --> PAST	288.0647	711.8222	0.43	74.01	
	Urban --> URBN	103.9881	256.9599	0.15	26.71	
SOILS:						
	I-Bc-L-2--640	392.0528	968.7820	0.58	100.72	
SLOPE:						
	20-40	74.0336	182.9407	0.11	19.02	
	0-20	318.0192	785.8414	0.47	81.70	
HRUs						
43	Pasture --> PAST/I-Bc-L-2--640/20-40	57.0336	140.9329	0.08	14.65	1
44	Pasture --> PAST/I-Bc-L-2--640/0-20	231.0311	570.8893	0.34	59.35	2
45	Urban --> URBN/I-Bc-L-2--640/20-40	17.0000	42.0078	0.03	4.37	3
46	Urban --> URBN/I-Bc-L-2--640/0-20	86.9882	214.9521	0.13	22.35	4
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	16	5554.7100	13725.9661	8.21		
LANDUSE:						
	Pasture --> PAST	5503.7865	13600.1317	8.14	99.08	
SOILS:						
	I-Bc-L-2--640	3689.0820	9115.9060	5.45	66.41	
	Ws13-2ab-985	1814.7046	4484.2257	2.68	32.67	
SLOPE:						
	0-20	3357.5800	8296.7481	4.96	60.45	
	20-40	1948.9182	4815.8743	2.88	35.09	
	40-60	197.2883	487.5093	0.29	3.55	
HRUs						
47	Pasture --> PAST/I-Bc-L-2--640/0-20	2358.9529	5829.0904	3.49	42.47	1
48	Pasture --> PAST/I-Bc-L-2--640/20-40	1330.1291	3286.8156	1.97	23.95	2
49	Pasture --> PAST/Ws13-2ab-985/0-20	998.6271	2467.6576	1.48	17.98	3
50	Pasture --> PAST/Ws13-2ab-985/20-40	618.7891	1529.0587	0.91	11.14	4
51	Pasture --> PAST/Ws13-2ab-985/40-60	197.2883	487.5093	0.29	3.55	5

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	17	323.9100	800.3978	0.48		
LANDUSE:						
	Pasture --> PAST	211.4136	522.4136	0.31	65.27	
	Urban --> URBN	114.8287	283.7475	0.17	35.45	
SOILS:						
	I-Bc-L-2--640	326.2423	806.1610	0.48	100.72	
SLOPE:						
	0-20	243.6415	602.0504	0.36	75.22	
	20-40	82.6008	204.1106	0.12	25.50	
HRUs						
52	Pasture --> PAST/I-Bc-L-2--640/0-20	144.7038	357.5704	0.21	44.67	1
53	Pasture --> PAST/I-Bc-L-2--640/20-40	66.7098	164.8432	0.10	20.60	2
54	Urban --> URBN/I-Bc-L-2--640/20-40	15.8910	39.2674	0.02	4.91	3
55	Urban --> URBN/I-Bc-L-2--640/0-20	98.9377	244.4801	0.15	30.54	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	18	698.4900	1726.0037	1.03		
LANDUSE:						
	Pasture --> PAST	500.1267	1235.8381	0.74	71.60	
	Urban --> URBN	203.3928	502.5937	0.30	29.12	
SOILS:						
	I-Bc-L-2--640	703.5195	1738.4318	1.04	100.72	
SLOPE:						
	20-40	205.2137	507.0933	0.30	29.38	
	0-20	498.3058	1231.3385	0.74	71.34	
HRUs						
56	Pasture --> PAST/I-Bc-L-2--640/20-40	171.3483	423.4102	0.25	24.53	1
57	Pasture --> PAST/I-Bc-L-2--640/0-20	328.7784	812.4279	0.49	47.07	2
58	Urban --> URBN/I-Bc-L-2--640/20-40	33.8654	83.6831	0.05	4.85	3
59	Urban --> URBN/I-Bc-L-2--640/0-20	169.5274	418.9106	0.25	24.27	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	19	7035.5700	17385.2452	10.40		
LANDUSE:						
	Pasture --> PAST	4859.8631	12008.9647	7.18	69.08	
	Urban --> URBN	1933.2106	4777.0600	2.86	27.48	
SOILS:						
	I-Bc-L-2--640	6793.0737	16786.0247	10.04	96.55	
SLOPE:						
	20-40	2217.7365	5480.1378	3.28	31.52	
	0-20	3623.7995	8954.5897	5.36	51.51	
	40-60	951.5377	2351.2971	1.41	13.52	
HRUs						
60	Pasture --> PAST/I-Bc-L-2--640/20-40	1988.9374	4914.7639	2.94	28.27	1
61	Pasture --> PAST/I-Bc-L-2--640/0-20	1919.3880	4742.9037	2.84	27.28	2
62	Pasture --> PAST/I-Bc-L-2--640/40-60	951.5377	2351.2971	1.41	13.52	3
63	Urban --> URBN/I-Bc-L-2--640/20-40	228.7991	565.3740	0.34	3.25	4
64	Urban --> URBN/I-Bc-L-2--640/0-20	1704.4115	4211.6860	2.52	24.23	5

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	20	4315.5000	10663.8163	6.38		
LANDUSE:						
	Pasture --> PAST	3274.2929	8090.9415	4.84	75.87	
	Urban --> URBN	1072.2807	2649.6593	1.58	24.85	
SOILS:						
	I-Bc-L-2--640	4346.5736	10740.6008	6.42	100.72	
SLOPE:						
	0-20	2779.8771	6869.2154	4.11	64.42	
	20-40	1566.6965	3871.3854	2.32	36.30	
HRUs						
65	Pasture --> PAST/I-Bc-L-2--640/0-20	1854.6778	4583.0016	2.74	42.98	1
66	Pasture --> PAST/I-Bc-L-2--640/20-40	1419.6151	3507.9399	2.10	32.90	2
67	Urban --> URBN/I-Bc-L-2--640/20-40	147.0814	363.4456	0.22	3.41	3
68	Urban --> URBN/I-Bc-L-2--640/0-20	925.1993	2286.2137	1.37	21.44	4

		Area [ha]	Area[acres]	%Nat.Area	%Sub.Area	
SUBBASIN #	21	1277.3700	3156.4451	1.89		
LANDUSE:						
	Pasture --> PAST	998.1505	2466.4798	1.48	78.14	
	Urban --> URBN	288.4171	712.6932	0.43	22.58	
SOILS:						
	I-Bc-L-2--640	1286.5677	3179.1730	1.90	100.72	
SLOPE:						
	20-40	525.4937	1298.5213	0.78	41.14	
	0-20	761.0739	1880.6518	1.12	59.58	
HRUs						
69	Pasture --> PAST/I-Bc-L-2--640/20-40	464.5733	1147.9838	0.69	36.37	1
70	Pasture --> PAST/I-Bc-L-2--640/0-20	533.5772	1318.4961	0.79	41.77	2
71	Urban --> URBN/I-Bc-L-2--640/20-40	60.9205	150.5375	0.09	4.77	3
72	Urban --> URBN/I-Bc-L-2--640/0-20	227.4967	562.1557	0.34	17.81	4
		Area [ha]	Area[acres]	%Nat.Area	%Sub.Area	
SUBBASIN #	22	3689.9100	9117.9521	5.45		
LANDUSE:						
	Pasture --> PAST	2779.3576	6867.9316	4.11	75.32	
	Urban --> URBN	937.1215	2315.6740	1.39	25.40	
SOILS:						
	I-Bc-L-2--640	3716.4791	9183.6057	5.49	100.72	
SLOPE:						
	0-20	1507.4783	3725.0542	2.23	40.85	
	60-80	319.6518	789.8756	0.47	8.66	
	40-60	750.1697	1853.7068	1.11	20.33	
	20-40	1139.1793	2814.9690	1.68	30.87	
HRUs						
73	Pasture --> PAST/I-Bc-L-2--640/0-20	741.7443	1832.8872	1.10	20.10	1
74	Pasture --> PAST/I-Bc-L-2--640/60-80	319.6518	789.8756	0.47	8.66	2
75	Pasture --> PAST/I-Bc-L-2--640/40-60	750.1697	1853.7068	1.11	20.33	3
76	Pasture --> PAST/I-Bc-L-2--640/20-40	967.7918	2391.4620	1.43	26.23	4
77	Urban --> URBN/I-Bc-L-2--640/0-20	765.7340	1892.1670	1.13	20.75	5
78	Urban --> URBN/I-Bc-L-2--640/20-40	171.3875	423.5070	0.25	4.64	6

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	23	2670.9300	6600.0016	3.95		
LANDUSE:						
	Pasture --> PAST	2688.9835	6644.6128	3.97	100.68	
SOILS:						
	I-Bc-L-2--640	2688.9835	6644.6128	3.97	100.68	
SLOPE:						
	60-80	301.1799	744.2305	0.45	11.28	
	40-60	798.1481	1972.2638	1.18	29.88	
	20-40	1015.6788	2509.7930	1.50	38.03	
	0-20	573.9768	1418.3255	0.85	21.49	
HRUs						
79	Pasture --> PAST/I-Bc-L-2--640/60-80	301.1799	744.2305	0.45	11.28	1
80	Pasture --> PAST/I-Bc-L-2--640/40-60	798.1481	1972.2638	1.18	29.88	2
81	Pasture --> PAST/I-Bc-L-2--640/20-40	1015.6788	2509.7930	1.50	38.03	3
82	Pasture --> PAST/I-Bc-L-2--640/0-20	573.9768	1418.3255	0.85	21.49	4
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	24	2794.5000	6905.3492	4.13		
LANDUSE:						
	Pasture --> PAST	2810.0893	6943.8712	4.15	100.56	
SOILS:						
	I-Bc-L-2--640	2810.0893	6943.8712	4.15	100.56	
SLOPE:						
	40-60	847.8173	2094.9989	1.25	30.34	
	20-40	927.3370	2291.4960	1.37	33.18	
	60-80	387.7390	958.1223	0.57	13.88	
	0-20	647.1961	1599.2540	0.96	23.16	
HRUs						
83	Pasture --> PAST/I-Bc-L-2--640/40-60	847.8173	2094.9989	1.25	30.34	1
84	Pasture --> PAST/I-Bc-L-2--640/20-40	927.3370	2291.4960	1.37	33.18	2
85	Pasture --> PAST/I-Bc-L-2--640/60-80	387.7390	958.1223	0.57	13.88	3
86	Pasture --> PAST/I-Bc-L-2--640/0-20	647.1961	1599.2540	0.96	23.16	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	25	6121.9800	15127.7187	9.05		
LANDUSE:						
	Pasture --> PAST	6098.6190	15069.9925	9.01	99.62	
SOILS:						
	I-Bc-L-2--640	6098.6190	15069.9925	9.01	99.62	
SLOPE:						
	20-40	2119.2186	5236.6951	3.13	34.62	
	60-80	981.7196	2425.8783	1.45	16.04	
	0-20	1284.8224	3174.8604	1.90	20.99	
	40-60	1712.8584	4232.5587	2.53	27.98	
HRUs						
87	Pasture --> PAST/I-Bc-L-2--640/20-40	2119.2186	5236.6951	3.13	34.62	1
88	Pasture --> PAST/I-Bc-L-2--640/60-80	981.7196	2425.8783	1.45	16.04	2
89	Pasture --> PAST/I-Bc-L-2--640/0-20	1284.8224	3174.8604	1.90	20.99	3
90	Pasture --> PAST/I-Bc-L-2--640/40-60	1712.8584	4232.5587	2.53	27.98	4

Appendix D: Final HRU land use, soil, and slope report (2018 LULC)

MULTIPLE HRUs LandUse/Soil/Slope OPTION

THRESHOLDS : 20 / 10 / 10 [%]

Number of HRUs: 92

Number of Subbasins: 25

		Area [ha]	Area[acres]			
Watershed		67654.2600	167177.0592			
		Area [ha]	Area[acres]	%Wat.Area		
LANDUSE:						
	Pasture --> PAST	52440.5032	129583.1055	77.51		
	Generic Agricultural Land --> AGRL	2076.8697	5132.0490	3.07		
	Urban --> URBN	13136.8870	32461.9047	19.42		
SOILS:						
	Ws13-2ab-985	15955.4956	39426.8275	23.58		
	I-Bc-L-2--640	51698.7644	127750.2317	76.42		
SLOPE:						
	0-20	40119.6871	99137.7528	59.30		
	20-40	18383.0854	45425.5232	27.17		
	40-60	6523.8383	16120.7306	9.64		
	60-80	2002.1498	4947.4124	2.96		
	80-9999	625.4994	1545.6403	0.92		
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	1	756.8100	1870.1154	1.12		
LANDUSE:						
	Pasture --> PAST	413.7548	1022.4089	0.61	54.67	
	Generic Agricultural Land --> AGRL	348.5045	861.1721	0.52	46.05	
SOILS:						
	Ws13-2ab-985	762.2594	1883.5811	1.13	100.72	
SLOPE:						
	0-20	762.2594	1883.5811	1.13	100.72	
HRUs						
1	Pasture --> PAST/Ws13-2ab-985/0-20	413.7548	1022.4089	0.61	54.67	1
2	Generic Agricultural Land --> AGRL/Ws13-2ab-985/0-20	348.5045	861.1721	0.52	46.05	2

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	2	1609.5600	3977.3032	2.38		
LANDUSE:						
	Pasture --> PAST	1621.1496	4005.9417	2.40	100.72	
SOILS:						
	Ws13-2ab-985	1621.1496	4005.9417	2.40	100.72	
SLOPE:						
	0-20	1621.1496	4005.9417	2.40	100.72	
HRUs						
3	Pasture --> PAST/Ws13-2ab-985/0-20	1621.1496	4005.9417	2.40	100.72	1
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	3	3414.3300	8436.9801	5.05		
LANDUSE:						
	Pasture --> PAST	2567.1817	6343.6343	3.79	75.19	
	Generic Agricultural Land --> AGRL	871.7331	2154.0961	1.29	25.53	
SOILS:						
	I-Bc-L-2--640	2233.2455	5518.4614	3.30	65.41	
	Ws13-2ab-985	1205.6692	2979.2690	1.78	35.31	
SLOPE:						
	0-20	3438.9148	8497.7304	5.08	100.72	
HRUs						
4	Pasture --> PAST/I-Bc-L-2--640/0-20	1602.2660	3959.2793	2.37	46.93	1
5	Pasture --> PAST/Ws13-2ab-985/0-20	964.9157	2384.3550	1.43	28.26	2
6	Generic Agricultural Land --> AGRL/I-Bc-L-2--640/0-20	630.9796	1559.1821	0.93	18.48	3
7	Generic Agricultural Land --> AGRL/Ws13-2ab-985/0-20	240.7535	594.9140	0.36	7.05	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	4	1831.9500	4526.8400	2.71		
LANDUSE:						
	Pasture --> PAST	1219.5217	3013.4991	1.80	66.57	
	Generic Agricultural Land --> AGRL	625.6192	1545.9364	0.92	34.15	
SOILS:						
	I-Bc-L-2--640	1364.6682	3372.1635	2.02	74.49	
	Ws13-2ab-985	480.4727	1187.2720	0.71	26.23	
SLOPE:						
	0-20	1657.9881	4096.9715	2.45	90.50	
	20-40	187.1528	462.4640	0.28	10.22	
HRUs						
8	Pasture --> PAST/I-Bc-L-2--640/0-20	634.6937	1568.3599	0.94	34.65	1
9	Pasture --> PAST/I-Bc-L-2--640/20-40	104.3553	257.8672	0.15	5.70	2
10	Pasture --> PAST/Ws13-2ab-985/0-20	397.6752	982.6752	0.59	21.71	3
11	Pasture --> PAST/Ws13-2ab-985/20-40	82.7975	204.5968	0.12	4.52	4
12	Generic Agricultural Land --> AGRL/I-Bc-L-2--640/0-20	625.6192	1545.9364	0.92	34.15	5
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	5	2437.7400	6023.7774	3.60		
LANDUSE:						
	Pasture --> PAST	2455.2929	6067.1515	3.63	100.72	
SOILS:						
	I-Bc-L-2--640	2455.2929	6067.1515	3.63	100.72	
SLOPE:						
	20-40	415.2514	1026.1069	0.61	17.03	
	0-20	2040.0415	5041.0446	3.02	83.69	
HRUs						
13	Pasture --> PAST/I-Bc-L-2--640/20-40	415.2514	1026.1069	0.61	17.03	1
14	Pasture --> PAST/I-Bc-L-2--640/0-20	2040.0415	5041.0446	3.02	83.69	2

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	6	3648.9600	9016.7626	5.39		
LANDUSE:						
	Pasture --> PAST	3675.2342	9081.6876	5.43	100.72	
SOILS:						
	Ws13-2ab-985	3675.2342	9081.6876	5.43	100.72	
SLOPE:						
	20-40	777.6355	1921.5761	1.15	21.31	
	0-20	2897.5988	7160.1115	4.28	79.41	
HRUs						
15	Pasture --> PAST/Ws13-2ab-985/20-40	777.6355	1921.5761	1.15	21.31	1
16	Pasture --> PAST/Ws13-2ab-985/0-20	2897.5988	7160.1115	4.28	79.41	2
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	7	1424.7000	3520.5049	2.11		
LANDUSE:						
	Pasture --> PAST	579.6243	1432.2806	0.86	40.68	
	Urban --> URBN	855.3342	2113.5736	1.26	60.04	
SOILS:						
	I-Bc-L-2--640	1109.1738	2740.8239	1.64	77.85	
	Ws13-2ab-985	325.7847	805.0303	0.48	22.87	
SLOPE:						
	0-20	1259.7403	3112.8812	1.86	88.42	
	20-40	175.2182	432.9730	0.26	12.30	
HRUs						
17	Pasture --> PAST/I-Bc-L-2--640/0-20	315.8816	780.5593	0.47	22.17	1
18	Pasture --> PAST/I-Bc-L-2--640/20-40	145.3081	359.0635	0.21	10.20	2
19	Pasture --> PAST/Ws13-2ab-985/20-40	29.9102	73.9095	0.04	2.10	3
20	Pasture --> PAST/Ws13-2ab-985/0-20	88.5244	218.7483	0.13	6.21	4
21	Urban --> URBN/I-Bc-L-2--640/0-20	647.9841	1601.2011	0.96	45.48	5
22	Urban --> URBN/Ws13-2ab-985/0-20	207.3501	512.3725	0.31	14.55	6

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	8	2234.6100	5521.8330	3.30		
LANDUSE:	Pasture --> PAST	2250.7002	5561.5928	3.33	100.72	
SOILS:	Ws13-2ab-985	2250.7002	5561.5928	3.33	100.72	
SLOPE:	20-40	882.1262	2179.7779	1.30	39.48	
	0-20	1368.5741	3381.8150	2.02	61.24	
HRUs						
23	Pasture --> PAST/Ws13-2ab-985/20-40	882.1262	2179.7779	1.30	39.48	1
24	Pasture --> PAST/Ws13-2ab-985/0-20	1368.5741	3381.8150	2.02	61.24	2
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	9	2182.6800	5393.5114	3.23		
LANDUSE:	Pasture --> PAST	2198.3963	5432.3472	3.25	100.72	
SOILS:	Ws13-2ab-985	2198.3963	5432.3472	3.25	100.72	
SLOPE:	0-20	1313.0809	3244.6885	1.94	60.16	
	20-40	885.3154	2187.6587	1.31	40.56	
HRUs						
25	Pasture --> PAST/Ws13-2ab-985/0-20	1313.0809	3244.6885	1.94	60.16	1
26	Pasture --> PAST/Ws13-2ab-985/20-40	885.3154	2187.6587	1.31	40.56	2
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	10	256.5000	633.8243	0.38		
LANDUSE:	Generic Agricultural Land --> AGRL	81.0521	200.2839	0.12	31.60	
	Urban --> URBN	177.2948	438.1043	0.26	69.12	
SOILS:	I-Bc-L-2--640	258.3469	638.3882	0.38	100.72	
SLOPE:	0-20	258.3469	638.3882	0.38	100.72	
HRUs						
27	Generic Agricultural Land --> AGRL/I-Bc-L-2--640/0-20	81.0521	200.2839	0.12	31.60	1
28	Urban --> URBN/I-Bc-L-2--640/0-20	177.2948	438.1043	0.26	69.12	2

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	11	360.8100	891.5796	0.53		
LANDUSE:						
	Urban --> URBN	363.4080	897.9993	0.54	100.72	
SOILS:						
	I-Bc-L-2--640	363.4080	897.9993	0.54	100.72	
SLOPE:						
	0-20	363.4080	897.9993	0.54	100.72	
HRUs						
29	Urban --> URBN/I-Bc-L-2--640/0-20	363.4080	897.9993	0.54	100.72	1
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	12	1726.0200	4265.0817	2.55		
LANDUSE:						
	Pasture --> PAST	466.3271	1152.3176	0.69	27.02	
	Urban --> URBN	1272.1211	3143.4747	1.88	73.70	
SOILS:						
	I-Bc-L-2--640	1738.4482	4295.7923	2.57	100.72	
SLOPE:						
	0-20	1366.1688	3375.8713	2.02	79.15	
	20-40	372.2794	919.9210	0.55	21.57	
HRUs						
30	Pasture --> PAST/I-Bc-L-2--640/0-20	259.9544	642.3604	0.38	15.06	1
31	Pasture --> PAST/I-Bc-L-2--640/20-40	206.3727	509.9572	0.31	11.96	2
32	Urban --> URBN/I-Bc-L-2--640/0-20	1106.2143	2733.5109	1.64	64.09	3
33	Urban --> URBN/I-Bc-L-2--640/20-40	165.9067	409.9638	0.25	9.61	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	13	7559.8200	18680.6932	11.17		
LANDUSE:						
	Pasture --> PAST	4572.0468	11297.7562	6.76	60.48	
	Urban --> URBN	3012.2936	7443.5282	4.45	39.85	
SOILS:						
	I-Bc-L-2--640	7584.3404	18741.2844	11.21	100.32	
SLOPE:						
	20-40	2454.8606	6066.0832	3.63	32.47	
	0-20	4335.7476	10713.8491	6.41	57.35	
	40-60	793.7322	1961.3520	1.17	10.50	
HRUs						
34	Pasture --> PAST/I-Bc-L-2--640/20-40	1853.5650	4580.2517	2.74	24.52	1
35	Pasture --> PAST/I-Bc-L-2--640/0-20	1924.7496	4756.1524	2.84	25.46	2
36	Pasture --> PAST/I-Bc-L-2--640/40-60	793.7322	1961.3520	1.17	10.50	3
37	Urban --> URBN/I-Bc-L-2--640/20-40	601.2956	1485.8315	0.89	7.95	4
38	Urban --> URBN/I-Bc-L-2--640/0-20	2410.9980	5957.6967	3.56	31.89	5
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	14	3337.6500	8247.5000	4.93		
LANDUSE:						
	Pasture --> PAST	820.2716	2026.9322	1.21	24.58	
	Urban --> URBN	2541.4110	6279.9537	3.76	76.14	
SOILS:						
	I-Bc-L-2--640	1666.1830	4117.2214	2.46	49.92	
	Ws13-2ab-985	1695.4997	4189.6645	2.51	50.80	
SLOPE:						
	20-40	271.6701	671.3104	0.40	8.14	
	0-20	2989.5934	7387.4348	4.42	89.57	
	40-60	100.4191	248.1407	0.15	3.01	
HRUs						
39	Pasture --> PAST/I-Bc-L-2--640/20-40	123.5281	305.2441	0.18	3.70	1
40	Pasture --> PAST/I-Bc-L-2--640/0-20	205.0178	506.6093	0.30	6.14	2
41	Pasture --> PAST/Ws13-2ab-985/0-20	243.1646	600.8718	0.36	7.29	3
42	Pasture --> PAST/Ws13-2ab-985/20-40	148.1420	366.0664	0.22	4.44	4
43	Pasture --> PAST/Ws13-2ab-985/40-60	100.4191	248.1407	0.15	3.01	5
44	Urban --> URBN/I-Bc-L-2--640/0-20	1337.6371	3305.3680	1.98	40.08	6
45	Urban --> URBN/Ws13-2ab-985/0-20	1203.7740	2974.5857	1.78	36.07	7

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	15	389.2500	961.8562	0.58		
LANDUSE:						
	Generic Agricultural Land --> AGRL	149.9607	370.5605	0.22	38.53	
	Urban --> URBN	242.0920	598.2215	0.36	62.19	
SOILS:						
	I-Bc-L-2--640	392.0528	968.7820	0.58	100.72	
SLOPE:						
	0-20	369.2206	912.3626	0.55	94.85	
	20-40	22.8322	56.4194	0.03	5.87	
HRUs						
46	Generic Agricultural Land --> AGRL/I-Bc-L-2--640/0-20	127.1286	314.1411	0.19	32.66	1
47	Generic Agricultural Land --> AGRL/I-Bc-L-2--640/20-40	22.8322	56.4194	0.03	5.87	2
48	Urban --> URBN/I-Bc-L-2--640/0-20	242.0920	598.2215	0.36	62.19	3
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	16	5554.7100	13725.9661	8.21		
LANDUSE:						
	Pasture --> PAST	5503.7865	13600.1317	8.14	99.08	
SOILS:						
	I-Bc-L-2--640	3763.4570	9299.6904	5.56	67.75	
	Ws13-2ab-985	1740.3296	4300.4413	2.57	31.33	
SLOPE:						
	20-40	2067.3654	5108.5634	3.06	37.22	
	0-20	3187.0697	7875.4086	4.71	57.38	
	40-60	249.3514	616.1598	0.37	4.49	
HRUs						
49	Pasture --> PAST/I-Bc-L-2--640/20-40	1463.0761	3615.3341	2.16	26.34	1
50	Pasture --> PAST/I-Bc-L-2--640/0-20	2300.3809	5684.3563	3.40	41.41	2
51	Pasture --> PAST/Ws13-2ab-985/40-60	249.3514	616.1598	0.37	4.49	3
52	Pasture --> PAST/Ws13-2ab-985/20-40	604.2894	1493.2293	0.89	10.88	4
53	Pasture --> PAST/Ws13-2ab-985/0-20	886.6888	2191.0523	1.31	15.96	5

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	17	323.9100	800.3978	0.48		
LANDUSE:						
	Pasture --> PAST	195.7695	483.7562	0.29	60.44	
	Urban --> URBN	130.4728	322.4049	0.19	40.28	
SOILS:						
	I-Bc-L-2--640	326.2423	806.1610	0.48	100.72	
SLOPE:						
	20-40	79.3819	196.1566	0.12	24.51	
	0-20	246.8604	610.0045	0.36	76.21	
HRUs						
54	Pasture --> PAST/I-Bc-L-2--640/20-40	60.7604	150.1420	0.09	18.76	1
55	Pasture --> PAST/I-Bc-L-2--640/0-20	135.0091	333.6142	0.20	41.68	2
56	Urban --> URBN/I-Bc-L-2--640/0-20	111.8514	276.3903	0.17	34.53	3
57	Urban --> URBN/I-Bc-L-2--640/20-40	18.6215	46.0146	0.03	5.75	4
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	18	698.4900	1726.0037	1.03		
LANDUSE:						
	Pasture --> PAST	343.6091	849.0753	0.51	49.19	
	Urban --> URBN	359.9103	889.3564	0.53	51.53	
SOILS:						
	I-Bc-L-2--640	703.5195	1738.4318	1.04	100.72	
SLOPE:						
	0-20	482.4435	1192.1420	0.71	69.07	
	20-40	221.0760	546.2897	0.33	31.65	
HRUs						
58	Pasture --> PAST/I-Bc-L-2--640/0-20	180.5497	446.1474	0.27	25.85	1
59	Pasture --> PAST/I-Bc-L-2--640/20-40	163.0594	402.9279	0.24	23.34	2
60	Urban --> URBN/I-Bc-L-2--640/20-40	58.0166	143.3618	0.09	8.31	3
61	Urban --> URBN/I-Bc-L-2--640/0-20	301.8938	745.9946	0.45	43.22	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	19	7035.5700	17385.2452	10.40		
LANDUSE:						
	Pasture --> PAST	4814.2394	11896.2263	7.12	68.43	
	Urban --> URBN	1978.8342	4889.7984	2.92	28.13	
SOILS:						
	I-Bc-L-2--640	6793.0737	16786.0247	10.04	96.55	
SLOPE:						
	40-60	1027.6311	2539.3278	1.52	14.61	
	0-20	3498.8012	8645.7127	5.17	49.73	
	20-40	2266.6413	5600.9841	3.35	32.22	
HRUs						
62	Pasture --> PAST/I-Bc-L-2--640/40-60	1027.6311	2539.3278	1.52	14.61	1
63	Pasture --> PAST/I-Bc-L-2--640/0-20	1759.3445	4347.4282	2.60	25.01	2
64	Pasture --> PAST/I-Bc-L-2--640/20-40	2027.2638	5009.4703	3.00	28.81	3
65	Urban --> URBN/I-Bc-L-2--640/20-40	239.3775	591.5138	0.35	3.40	4
66	Urban --> URBN/I-Bc-L-2--640/0-20	1739.4567	4298.2845	2.57	24.72	5
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	20	4315.5000	10663.8163	6.38		
LANDUSE:						
	Pasture --> PAST	3122.6676	7716.2679	4.62	72.36	
	Urban --> URBN	1223.9060	3024.3329	1.81	28.36	
SOILS:						
	I-Bc-L-2--640	4346.5736	10740.6008	6.42	100.72	
SLOPE:						
	20-40	1686.8456	4168.2798	2.49	39.09	
	0-20	2659.7280	6572.3210	3.93	61.63	
HRUs						
67	Pasture --> PAST/I-Bc-L-2--640/20-40	1521.9980	3760.9332	2.25	35.27	1
68	Pasture --> PAST/I-Bc-L-2--640/0-20	1600.6696	3955.3347	2.37	37.09	2
69	Urban --> URBN/I-Bc-L-2--640/20-40	164.8476	407.3466	0.24	3.82	3
70	Urban --> URBN/I-Bc-L-2--640/0-20	1059.0584	2616.9863	1.57	24.54	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	21	1277.3700	3156.4451	1.89		
LANDUSE:						
	Pasture --> PAST	1286.5677	3179.1730	1.90	100.72	
SOILS:						
	I-Bc-L-2--640	1286.5677	3179.1730	1.90	100.72	
SLOPE:						
	40-60	149.1266	368.4992	0.22	11.67	
	0-20	571.9721	1413.3716	0.85	44.78	
	20-40	565.4690	1397.3022	0.84	44.27	
HRUs						
71	Pasture --> PAST/I-Bc-L-2--640/40-60	149.1266	368.4992	0.22	11.67	1
72	Pasture --> PAST/I-Bc-L-2--640/0-20	571.9721	1413.3716	0.85	44.78	2
73	Pasture --> PAST/I-Bc-L-2--640/20-40	565.4690	1397.3022	0.84	44.27	3
		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	22	3689.9100	9117.9521	5.45		
LANDUSE:						
	Pasture --> PAST	2736.6702	6762.4489	4.05	74.17	
	Urban --> URBN	979.8089	2421.1567	1.45	26.55	
SOILS:						
	I-Bc-L-2--640	3716.4791	9183.6057	5.49	100.72	
SLOPE:						
	40-60	790.4415	1953.2204	1.17	21.42	
	60-80	333.9148	825.1203	0.49	9.05	
	20-40	1157.0449	2859.1158	1.71	31.36	
	0-20	1435.0779	3546.1492	2.12	38.89	
HRUs						
74	Pasture --> PAST/I-Bc-L-2--640/40-60	790.4415	1953.2204	1.17	21.42	1
75	Pasture --> PAST/I-Bc-L-2--640/60-80	333.9148	825.1203	0.49	9.05	2
76	Pasture --> PAST/I-Bc-L-2--640/20-40	973.7368	2406.1522	1.44	26.39	3
77	Pasture --> PAST/I-Bc-L-2--640/0-20	638.5771	1577.9560	0.94	17.31	4
78	Urban --> URBN/I-Bc-L-2--640/0-20	796.5008	1968.1932	1.18	21.59	5
79	Urban --> URBN/I-Bc-L-2--640/20-40	183.3081	452.9635	0.27	4.97	6

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	23	2670.9300	6600.0016	3.95		
LANDUSE:						
	Pasture --> PAST	2688.9835	6644.6128	3.97	100.68	
SOILS:						
	I-Bc-L-2--640	2688.9835	6644.6128	3.97	100.68	
SLOPE:						
	40-60	867.3449	2143.2527	1.28	32.47	
	0-20	452.5621	1118.3036	0.67	16.94	
	20-40	1053.1965	2602.5012	1.56	39.43	
	60-80	315.8800	780.5553	0.47	11.83	
HRUs						
80	Pasture --> PAST/I-Bc-L-2--640/40-60	867.3449	2143.2527	1.28	32.47	1
81	Pasture --> PAST/I-Bc-L-2--640/0-20	452.5621	1118.3036	0.67	16.94	2
82	Pasture --> PAST/I-Bc-L-2--640/20-40	1053.1965	2602.5012	1.56	39.43	3
83	Pasture --> PAST/I-Bc-L-2--640/60-80	315.8800	780.5553	0.47	11.83	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	24	2794.5000	6905.3492	4.13		
LANDUSE:						
	Pasture --> PAST	2810.0893	6943.8712	4.15	100.56	
SOILS:						
	I-Bc-L-2--640	2810.0893	6943.8712	4.15	100.56	
SLOPE:						
	0-20	484.3604	1196.8789	0.72	17.33	
	40-60	941.5648	2326.6536	1.39	33.69	
	20-40	958.6800	2368.9462	1.42	34.31	
	60-80	425.4841	1051.3925	0.63	15.23	
HRUs						
84	Pasture --> PAST/I-Bc-L-2--640/0-20	484.3604	1196.8789	0.72	17.33	1
85	Pasture --> PAST/I-Bc-L-2--640/40-60	941.5648	2326.6536	1.39	33.69	2
86	Pasture --> PAST/I-Bc-L-2--640/20-40	958.6800	2368.9462	1.42	34.31	3
87	Pasture --> PAST/I-Bc-L-2--640/60-80	425.4841	1051.3925	0.63	15.23	4

		Area [ha]	Area[acres]	%Wat.Area	%Sub.Area	
SUBBASIN #	25	6121.9800	15127.7187	9.05		
LANDUSE:						
	Pasture --> PAST	6098.6190	15069.9925	9.01	99.62	
SOILS:						
	I-Bc-L-2--640	6098.6190	15069.9925	9.01	99.62	
SLOPE:						
	80-9999	625.4994	1545.6403	0.92	10.22	
	0-20	1058.9789	2616.7899	1.57	17.30	
	20-40	1883.0431	4653.0938	2.78	30.76	
	40-60	1604.2267	3964.1244	2.37	26.20	
	60-80	926.8709	2290.3443	1.37	15.14	
HRUs						
88	Pasture --> PAST/I-Bc-L-2--640/80-9999	625.4994	1545.6403	0.92	10.22	1
89	Pasture --> PAST/I-Bc-L-2--640/0-20	1058.9789	2616.7899	1.57	17.30	2
90	Pasture --> PAST/I-Bc-L-2--640/20-40	1883.0431	4653.0938	2.78	30.76	3
91	Pasture --> PAST/I-Bc-L-2--640/40-60	1604.2267	3964.1244	2.37	26.20	4
92	Pasture --> PAST/I-Bc-L-2--640/60-80	926.8709	2290.3443	1.37	15.14	5

Appendix F: 2018 annual water balance report generated by ArcSWAT

✓ SWAT Error Checker - Version 1.2.0.10 Released November 6, 2018

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