Application of the SWAT hydrological model in a small, mountainous catchment in South Africa

by

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DECLARATION

I, Kimberley Anne Perry, declare that the dissertation, which I hereby submit for the degree Master of Science in Water Resource Management at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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SUMMARY

Natural water resources are globally under pressure due to increasing population numbers and associated global change drivers, such as land-use and climate change. South Africa has a semi-arid climate, with variable patterns of rainfall and is often referred to as a water scarce country. Much of South Africa's fresh water originates in mountainous areas. It is important to correctly manage these mountainous areas and the fresh water resources they provide. Hydrological models could be a useful tool aiding water resource managers in accurately assessing and predicting hydrological processes in mountainous regions. Hydrological models can be used to predict the effect that changes in a catchment area, such as land use or climate change, will have on the associated water resources in the catchment.

The aim of this study was to determine if the SWAT hydrological model could successfully simulate runoff from a small, mountainous catchment in South Africa. The SWAT model was applied to the B73A quaternary catchment located east of the Blyde River Canyon, close to Hoedspruit. This catchment is highly mountainous in nature. Observed stream flow data was obtained from the Department of Water and Sanitation (DWS) at a stream gauge located in the catchment. This observed data was used to calibrate and validate the model, using Sequential Uncertainty Fitting (SUFI-2) in the SWAT-CUP program.

Results from calibration show good agreement between observed and simulated monthly stream flow data (NSE= 0.80). The model was able to bracket 68% of observed data in a small uncertainty band (r-factor = 0.67). The model was then validated using the same observed stream flow data during a different time period. Results for validation were again adequate (NSE= 0.46). In this case the model bracketed 71% of the data in a slightly larger uncertainty band (r-factor = 1.12).

The study illustrates the potential of the SWAT hydrological model to be used in mountainous, semi-arid catchment areas in South Africa. Despite limited climate data and soil data, as well as the use of only one stream flow gauge location of observed data during calibration, which limited the incorporation of spatial variability within the catchment area into the model. Reliable rainfall data was obtained in the form of a rainfall station in the study area, highlighting the importance of this input variable in the SWAT model. Also highlighted was the need for appropriate calibration procedures to accurately represent the local characteristics of the modelled area.

It was concluded that the SWAT hydrological model was able to adequately simulate the stream flow data from the B73A quaternary catchment area. This model could be a useful tool in predicting the effect of future land use and climate change scenarios on stream flow from the B73A quaternary catchment. It could be used for water resource management in this catchment.

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LIST OF ACRONYMS

AGRL:	Agricultural Land – Generic
AGRR:	Agricultural Land – Rows Crops
ARC:	Agricultural Research Institute: Institute of Soil, Water and Climate
ARS:	Agricultural Research Service
CFSR:	Climate Forecast System Reanalysis
DEM:	Digital Elevation Model
DWS:	Department of Water and Sanitation
ESRI:	Environmental Systems Research Institute
FRSE:	Evergreen Forests
GIS:	Geographic Information Systems
GPS:	Global Positioning System
HRU:	Hydrological Response Unit
MAP:	Mean Annual Precipitation
MAE:	Mean Annual Evaporation
MASL:	Metres above Sea Level
NCEP:	National Centre for Environmental Prediction
NSE:	Nash-Sutcliffe Efficiency
PAST:	Pastures
PBIAS:	Percent BIAS
RNGE:	Disturbed Lands
RBHNR:	Revised Broad Homogeneous Natural Regions
SANBI:	South African National Biodiversity Institute
SWAT:	The Soil and Water Assessment Tool
SUFI-2:	Sequential Uncertainty Fitting version 2
UIDU:	Industrial areas

URBN: Residential

USDA: United States Department of Agriculture

WATR: Water

WRC: Water Research Commission

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CHAPTER 1: INTRODUCTION

1.1. LITERATURE REVIEW

1.1.1. Background

It was previously found that mountainous areas have a major impact on the climate, and subsequently the water resources, of an area (Viviroli *et al*, 2011). Mountain ranges force air to lift. As the air lifts it cools and condenses, producing precipitation. This type of precipitation is known as 'orographic precipitation'. Orographic precipitation can contribute to substantial amounts of stream flow in river basins (Viviroli *et al*, 2003; Messerli *et al*, 2004; Viviroli and Weingartner, 2004; Viviroli *et al*, 2007). As a result, many rivers throughout the world have their source in a mountainous region (Alford, 1985; Viviroli and Weingartner, 2004; Roe, 2005).

Mountainous regions are important as they provide freshwater resources to the surrounding lowland areas, as well as to the mountain ecosystems themselves (Viviroli *et al*, 2003; Messerli *et al*, 2004; Viviroli and Weingartner, 2004; Viviroli *et al*, 2007). A single mountain, due to short elevational distances, is able to host a number of climatically different life zones (Körner, 2004). Mountains are therefore often hotspots of biodiversity (Körner, 2004). This biodiversity plays a crucial role in safeguarding the ecosystem services that a mountain system supplies, such as the provision and regulation of freshwater resources (Postel and Thompson, 2005). The freshwater resources that originate in mountainous regions currently provide approximately 700 million people worldwide who live in mountainous areas with water (Messerli *et al*, 2004). Additionally, there are numerous lowland populations that indirectly rely on the functional integrity of mountain ecosystems for their water supply (Körner, 2004).

Despite the fact that these mountainous regions, specifically those that are over 1000 Metres Above Mean Sea Level (MASL), make up only 27% of the Earth's continental surface, they contribute disproportionately large amounts of water to their surrounding lowland areas (Alford, 1985; Barros and Lettenmaier, 1993; Ives *et al*, 1997; Viviroli *et al*, 2003; Messerli *et al*, 2004; Viviroli *et al*, 2007). This has resulted in the use of the term "water towers" to describe mountainous regions (Alford, 1985; Barros and Lettenmaier, 1993; Ives *et al*, 1997; Viviroli *et al*, 2003; Messerli *et al*, 2004; Viviroli *et al*, 2007).

These mountainous areas, or water towers of the world, are expected to become increasingly vulnerable as a result of ongoing global change (Schröter *et al*, 2005). Global change drivers include the rapidly increasing human population growth rate and associated resource consumption, energy use, climate change, land use change and pollution (Vitousek, 1994; Messerli *et al*, 2004). In certain areas global change is expected to lead to a decrease in the supply of ecosystem services, such as water provision and availability (Schröter *et al*, 2005). Water towers are therefore expected to become the source of competing uses of water, such as irrigation, drinking, hydropower, industrial uses, and partly also recreational purposes (Alford, 1985; Viviroli *et al*, 2003; Messerli *et al*, 2004).

To predict the effects of global change on water supply, knowledge regarding the availability of freshwater from water towers must increase. This essentially needs research that focuses on mountainous areas (Kundzewicz, 1997). Despite the acknowledged need for this research, there is often a lack of long-term data from these areas (Gurtz *et al*, 2003). This is due to the numerous challenges associated with data collection in mountainous areas (Klemes, 1990). Some of these challenges include accessibility on a continuous basis into the mountains, accuracy of measurements and representativeness of observations from these areas (Klemes, 1990). The complexity of mountain environments adds to the challenge of understanding mountain hydrology. Rainfall events can be isolated temporally and spatially, making them difficult to record. Many different processes can be activated in mountainous watersheds such as evapotranspiration, surface runoff, sub-surface runoff, ground-water flow and snow dynamics. All of these processes are potentially hard to quantify and measure (Chaponniere *et al*, 2008).

1.1.2. Modelling the hydrological system

Hydrological modelling may be used as an effective tool to gather information and knowledge about the hydrology of mountainous areas (Klemes, 1990; Hartman *et al*, 1999; Gurtz *et al*, 2003; Viviroli and Weingartner, 2004; Chaponniere *et al*, 2008). Hydrological models, as defined by Hughes (2004) are 'simplified, conceptual representations of the different parts of the hydrological cycle using mathematical representations of the processes involved in the transformation of climate inputs - precipitation, solar energy and wind – through surface and subsurface transfers of water and energy into hydrological outputs (typically, flow in rivers, soil moisture content or water levels in groundwater aquifers)’. The fundamental objective of hydrological modelling has been defined as a way to gain understanding of the hydrological system, thereby providing reliable information for managing water resources in a sustained manner to increase human welfare and protect the environment (Hughes *et al*, 2003). Hydrological models can be used to aid management of catchments and watersheds, and has the potential to become common planning or decision making tools (Arnold *et al*, 1998).

Hydrological models were first developed in the 1930s. Initially they were event-based representations, which could be used with hand calculation (Wheater, 2005). Following an increase in computational power, hydrological models were able to become more conceptually complex, i.e. physics-based (Beven, 1989; Hughes, 2004; Wheater, 2005). Mathematical algorithms that represent physical and hydrological processes were developed and incorporated into the models, allowing them to better represent process hydrology. For a complex environment, such as a mountainous area, this is beneficial. Figure 1.1 illustrates a summarized view of the development of hydrological models from the 1930s.

Physics-based models, however, are not without their own problems. More complex models require more parameters. Parameters, as defined by Wheater (2005), are numerical measures of a property or characteristic which are constant under specified conditions. Physics-based models attempt to represent the individual processes involved in the water cycle, which subsequently require more parameters (Figure 1.1). Parameters need to be quantified, therefore the development of models that contain a larger number of parameters require greater resources of time, effort and information (Xu and Singh, 1998; Hughes, 2004). There is also the question as to how adequately mathematical algorithms, which are developed by small-scale field or lab studies, can represent hydrological processes which occur at much larger spatial scale in reality (Beven, 1989; Hughes, 1989; Blöschl and Sivalapan, 1995). The success of these models to produce adequate results, in effect, depends on the ability of the model developer to understand the way hydrological processes interact, and to subsequently translate these processes into mathematical equations (model algorithms) (Hughes, 2004).

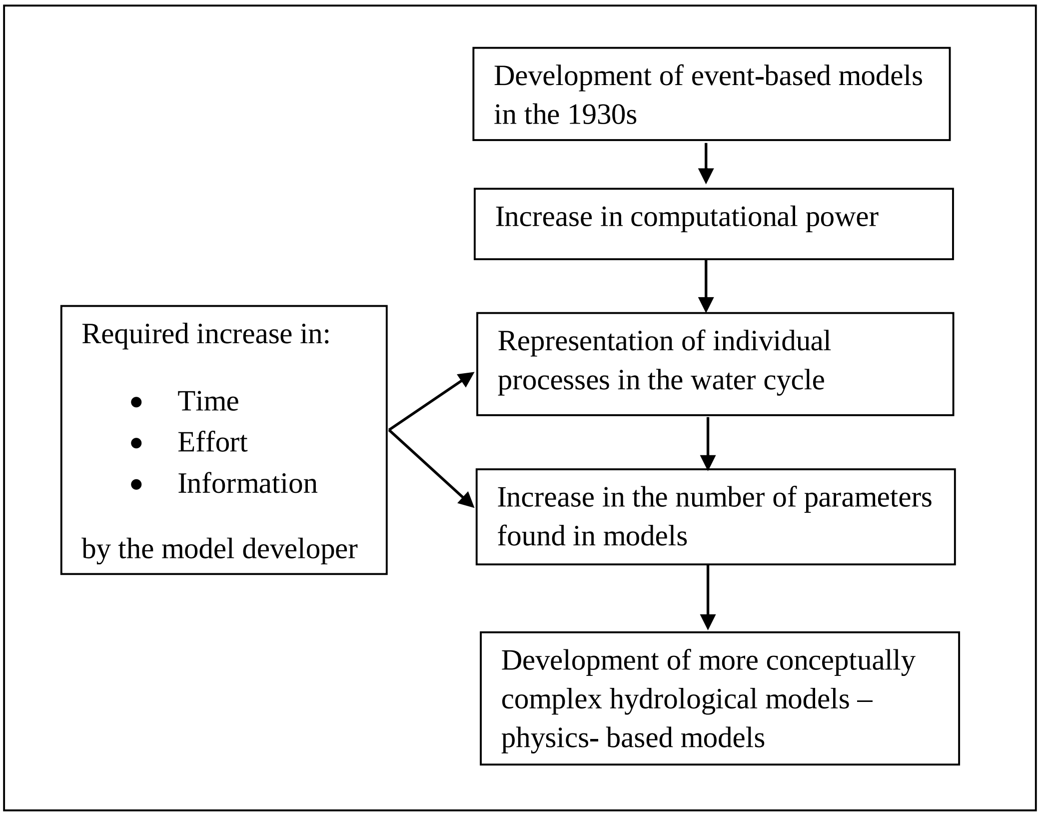


Figure 1.1. Development of hydrological models since the 1930's, from event-based to more conceptually complex physics-based models.

Hydrological models can become more complex in terms of temporal and spatial complexity. More temporally complex models use, for example, hourly or daily inputs whereas the simpler models make use of monthly time intervals (Xu and Singh, 1998; Hughes, 2004). In terms of spatial complexity, Hughes (2004) states that more spatially complex models 'disaggregate the total area to be modelled into a number of sub-areas based on natural drainage units (such as slopes, channels, catchments), or on geometric shapes (square grids, polygons, etc.)'. If a model is more complex, either by containing a large number of parameters or by being spatially or temporally complex, it will require data that is essentially of a greater quality or quantity. This can prove to be problematic in mountainous areas where, as previously discussed, data can be scarce (Chaponniere *et al*, 2008).

Hughes (2004) points out that 'initially, computational power constrained the development and application of models - whereas now the main constraint can be seen as information availability.' This problematic lack of data, which is so applicable in mountainous areas, can be potentially resolved by software developments, in particular Geographic Information Systems (GIS). GIS have gone a long way to enable hydrological models to become more user-friendly. With GIS-based techniques for interfacing a model with data, as well as a wider use and application of remote sensing, models in future will be less constrained by data. However, users should be aware of the limitations when practical application of any hydrological model is done. Xu and Singh (1998) emphasize this when they state 'any individual model user is therefore faced with a choice of using either a sophisticated model with less than perfect input data or a less complex model, based upon a simpler conceptualization of "known reality", for which data requirements are less stringent.'

An example of a widely used hydrological model that uses GIS for interfacing a model with data is the Soil and Water Assessment Tool (SWAT) hydrological model. The SWAT model is the result of roughly 30 years of modelling experience and research at the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) in Texas, America (Arnold *et al*, 1998). The model is physically-based, implying that it simulates actual hydrological processes such as stream flow, runoff, tillage and crop growth. It therefore requires detailed climatic and geographic information about the area being modelled (Arnold *et al*, 1998; Gassman *et al*, 2007). It is able to continuously simulate certain conditions over long time periods. This model was developed to predict the impact that managing catchment areas would have on water yield, as well as sediment and agricultural chemical yields (Arnold *et al*, 1998; Gassman *et al*, 2007).

There is an abundance of studies that have been conducted using the SWAT model to simulate hydrological processes. Ridwansyah *et al* (2014) modelled a mountainous catchment in Indonesia using SWAT. The study found there was good potential for the SWAT model to be used as a monitoring tool in mountainous watershed management (Ridwansyah *et al*, 2014). Four sub-watersheds in the Sandusky watershed in Ohio were modelled using SWAT and the simulated trends were found to match moderately well with observed data (Qi and Grunwald, 2005). Noor *et al* (2014) modelled the hydrology in the Taleghan mountains, Iran, and found that SWAT provided reasonable predictions of daily stream flow.

In Africa, studies applying the SWAT model to simulate mountainous catchments have been more limited. Birhanu *et al* (2007) examined the applicability of the SWAT model to simulate flow in mountainous catchments, specifically the WeruWeru catchment in the Kilimanjaro region of Northern Tanzania. The study found that the model performed well and highlighted the potential of SWAT to model mountainous catchments (Birhanu *et al*, 2007). The SWAT model was applied in a tropical mountainous catchment in Eastern Uganda. The model performed satisfactorily in simulating monthly stream flow, but had a tendency to under predict daily peak flows (Mutenyo *et al*, 2013).

Govender and Everson (2005) used the SWAT model to simulate hydrological processes in the KwaZulu Natal Drakensburg mountains in South Africa. The study focused on two mountainous catchments that had different land covers, namely grassland and pine plantation. The model adequately predicted stream flow for the grassland catchment, but over simulated the flow for the *Pinus patula* afforested catchment. This was explained to be due to the model not accounting for the increase in evapotranspiration as the pine plantations matured over time (Govender and Everson, 2005).

1.2. RATIONALE FOR THE STUDY

There is an acknowledged need to undergo further research into the supply and integrity of the water resources that mountainous areas provide, due to the fact that they contribute disproportionate amounts of water to downstream areas (Barros and Lettenmaier, 1993; Ives *et al*, 1997; Gurtz *et al*, 2003; Viviroli *et al*, 2003; Viviroli and Weingartner, 2004; Messerli *et al*, 2004; Viviroli *et al*, 2007; Turpie *et al*, 2008). Mountains have been shown to contribute over 95% of total discharge in arid and semi-arid areas, such as Southern Africa (Gurtz *et al*, 2003; Viviroli *et al*, 2003; Messerli *et al*, 2004; Viviroli *et al*, 2007). Figure 1.2 illustrates the areas of high water yield across South Africa (Driver *et al*, 2004). Most of South Africa's surface water originates from the Drakensberg mountain range (including the Maloti mountains of Lesotho), and the Cape mountains (Turpie *et al*, 2008). The management of these mountain regions, and the water resources that they provide, will become essential to ensure a safe and reliable supply of water in years to come.

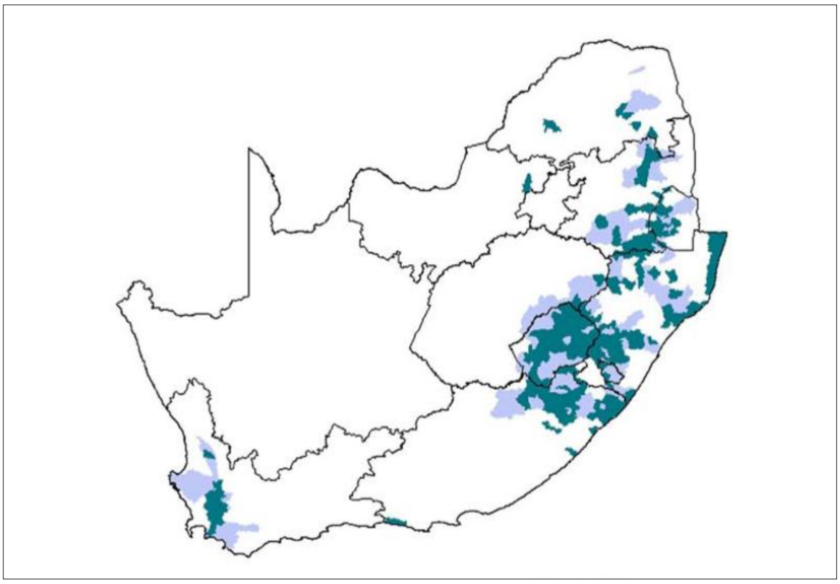


Figure 1.2. Areas of high water yield across South Africa which are mostly associated with high topography or mountains (Source: Driver *et al*, 2004).

The use of hydrological models in South Africa has the potential to address emerging issues in water resource estimation and management (Kapangaziwiri *et al*, 2013). The 1990 Surface Water Resources of South Africa Study (WR90) illustrates just how effective hydrological modelling can be in water resource management. The project generated information, such as land cover, rainfall, recorded and simulated run-off, at quaternary level for the whole of South Africa, Lesotho and Swaziland. The products that were generated from the WR90 study have become essential for water resources management, planning and operational practitioners, researchers and decision makers. The Water Resources of South Africa, 2005 study (WR2005) was commissioned by the Water Research Commission (WRC) in 2004. This project was similar to the WR90 study, but with the use of updated data, as well as conducted with a more integrated perspective.

There are limited studies in South Africa which focus on mountainous regions and even fewer which specifically use the SWAT model as a management tool in mountainous catchments. This study will assess the applicability of the SWAT model in a small mountainous South African catchment. The catchment chosen to be used as the study area is the B73A quaternary catchment, in accordance to the South African Department of Water and Sanitation (DWS) referencing system.

The B73A quaternary catchment forms part of the Olifants (North) primary catchment area. It is located east of the Blyde River Canyon, close to Hoedspruit. The river flowing through the catchment is the Klaserie river. It varies considerably in altitudinal range, from lowland grassland areas located at 548 MASL to the top of the Mariepskop mountain at an altitude of 1901 MASL (Van der Schijff and Schoonraad, 1971). This altitudinal range makes it an ideal study area to be used for examining the applicability of the SWAT model on a mountainous catchment area. Table 1 gives a brief description of the characteristics of the study area.

Table 1. Brief description of the B73A quaternary catchment area.

Spatial coverage of the catchment area:	165km^2
Location:	30˚85'E - 31˚08'E and 24˚52' - 24˚66'S
Mean annual rainfall:	1369mm
Altitude range:	548 – 1901 MASL

1.3. AIM AND OBJECTIVES OF THE STUDY

1.3.1. Aim

This study focuses on the water resources associated with mountainous regions, as well as the importance of managing these resources. Water resource management encompasses the whole catchment area, from the source to the water users. The water quality and quantity originating from the source, usually mountainous areas, will affect the water reaching the downstream users. Hydrological modelling can potentially be a useful tool to aid in the management of mountainous water resources. The aim of the study is to examine the hydrology of a small, mountainous catchment in South Africa using a hydrological model.

1.3.2. Objectives

- Objective 1: Describe the B73A quaternary catchment domain in South Africa to which the SWAT model will be applied.

This will be achieved by site visits to the chosen study area and by researching previous studies conducted in the study area.

- Objective 2: Apply the SWAT hydrological model to the B73A quaternary catchment.

The model will be setup using GIS data specific to the study catchment area.

- Objective 3: Determine applicability of the SWAT hydrological model to the mountainous B73A quaternary catchment for providing information for water resource management.

The model will be calibrated and validated using observed stream flow data from a particular outlet found in the catchment. The model can then be used to simulate the runoff, and subsequent stream flow, from the mountainous catchment area. It has the potential to be an invaluable tool which will aid in the management of freshwater resources originating from the mountain.

1.4. ORGANISATION OF THE DISSERTATION

Following the introduction in Chapter one, the thesis will be organised as follows. Chapter two will describe the study area. This chapter will include a description of the climate, geology, soils, vegetation and land cover of the study catchment, as well as a short description of the activities in the study area.

Chapter three describes the process involved in the collection of the datasets which are needed for the hydrological modelling with the Soil and Water Assessment Tool (SWAT) model. The main datasets needed include geographical, climate and stream flow data.

Chapter four describes in detail the processes that are involved in the modelling of the B73A quaternary catchment with SWAT. Initially the model must be setup during a number of different stages. Each of the stages involved in the setup of the model are described in subsections of the chapter. These include: the watershed delineation process; soil, land use and slope definition and overlay; Hydrological Response Unit (HRU) definition; weather data definition and writing the input files. The chapter ends with a description on how the model is subsequently run.

Chapter five includes a description of the processes of calibrating and validating a model. This includes the process of choosing parameters that are considered important to calibrate. Global sensitivity analysis is explained. The process of manual calibrating the model was briefly described. This chapter also provides an overview on how the model will be assessed. In particular the chapter focuses on the conceptual basis of the SUFI-2 program which was used to further calibrate the model, and used for the validation process.

Chapter six describes the results and discusses the applicability of these results in the specific B73A catchment area. These results include the results of the initial analysis, manual calibration results, global sensitivity analysis results and the results of using the SUFI-2 program for calibration and validation. It compares these results with previous studies that have used the SWAT model in mountainous areas.

Chapter seven concludes the dissertation, and contains some recommendations found during the course of the project.

CHAPTER 2: STUDY AREA

2.1. DESCRIPTION OF THE STUDY AREA

The study area is the B73A quaternary catchment, in accordance to the South African DWS referencing system. The B73A quaternary catchment forms part of the Olifants (North) primary catchment area (Figure 2.1). The catchment is located east of the Blyde River Canyon, close to Hoedspruit. Geographically, the catchment lies between 30˚ 85’ - 31˚ 08’ E and 24˚ 52’ - 24˚ 66’ S. The altitude ranges from 548 to 1901 m, with an approximate drainage area of 165 km^2. The outlet of the study area is the Jan Wassenaar Dam. The main river in the catchment is the Klaserie River, which is approximately 28.862 km in length from its source to the Jan Wassenaar Dam. The full length of the Klaserie River, from its source to its confluence with the Olifants River is 113.6916 km in length.

The highest altitude found in the catchment is situated near the top of the Mariepskop mountain. The Mariepskop mountain is situated on the eastern side of the Drakensberg Escarpment, in the Mpumalanga Province of South Africa. Mariepskop mountain forms part of the Mariepskop-Magalieskop complex. The Mariepskop mountain is the highest peak in the northern Drakensburg escarpment, with an altitude of 1946 MASL (Van der Schijff and Schoonraad, 1971). The mountain is an ideal example of a water tower due to its height, as well as the fact that the Mariepskop-Magalieskop complex itself is an orographically isolated area. Since the complex is separated from the rest of the Drakensberg Range by a tributary of the Klaserie River and by the Blyde River, which both form a deep canyon (Van der Schijff and Schoonraad, 1971).

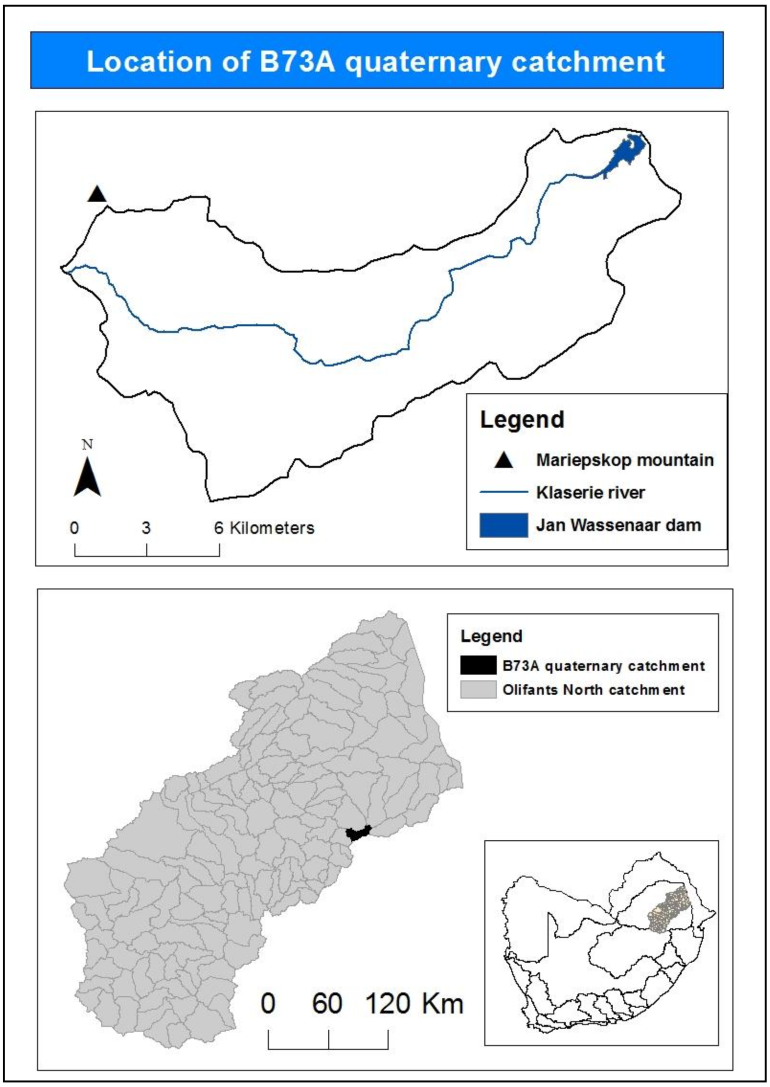


Figure 2.1. Location of B73A quaternary catchment relative to the Olifants North catchment and South Africa. The Klaserie river and Jan Wassenaar dam are shown in blue in the top figure.

2.1.1. Climate

The rainfall distribution in the B73A quaternary catchment varies considerably from the higher altitudes in the mountainous regions to the lowland areas. The mean annual rainfall of the Mariepskop mountain has previously been measured as 1369 mm, falling mainly in the summer months (Van der Schijff and Schoonraad, 1971). In other areas on the mountain, such as the sheltered kloofs facing east and south-east, precipitation might be much higher judging by the vegetation present in those areas (Van der Schijff and Schoonraad, 1971). Figure 2.2 and Figure 2.3 shows the cloud cover that can accumulate as air is forced to rise against the mountains in the B73A quaternary catchment. The majority of the catchment found in the mountainous regions experiences a Mean Annual Precipitation (MAP) of between 1000-1500 mm, although some areas are recorded to experience more than 1500mm (WR2005b). The majority of the low-lying regions of the catchment experience a MAP of between 600-700mm (WR2005b). The study area experiences a MAP of 957mm (WR2005a). Mean Annual Evaporation (MAE) is 1444mm (WR2005a). Mean annual run-off has been previously measured as 184.2mm (WR2005b).

Figure 2.2. An image of the cloud cover accumulating against the mountains in the B73A quaternary catchment.

Figure 2.3. An image of the cloud cover accumulating against the mountains in the B73A quaternary catchment.

2.1.2. Geology

The simplified geology of the study area is mainly comprised of acid and intermediate extrusives, as well as intercalated assemblages of compact sedimentary and extrusive rocks (DWS, 2013; WR2005b). Mariepskop mountain is partly formed of the erosion-resisting quartzites of the Black Reef Series which consists of a succession of quartzites, sandstones, conglomerates and sandy shales (Van der Schijff and Schoonraad, 1971). According to McCartney *et al* (2004), the catchment geology is Granite, Granodiorite, tonalite, gneiss and migmatite.

2.1.3. Soils

Soil data from the Water Resources of South Africa, 2005 study (WR2005) is based on the 1989 Revised Broad Homogeneous Natural Regions (RBHNR) map produced by the Department of Agricultural Engineering, University of Natal, Pietermaritzburg. The majority of the study area has moderate to deep sandy loam soils, found on undulating relief (WR2005b). The soils found at the higher altitudes, and on steeper slopes compared to the lowland areas of the catchment, have a clayey loam texture and are of moderate to deep depth (WR2005b), belonging to the Lateritic Red Earths (Van der Schijff and Schoonraad, 1971). Van der Schijff and Schoonraad (1971) describe the mature soils as strongly weathered and deep, with the mineral content generally low. Furthermore, Van der Schijff and Schoonraad (1971) state that 'horizon development is poor, but the soil is well-drained. The soils of the higher areas with a higher rainfall are more leached and laterized than those in the Blyde River Canyon and at the foothills of the mountain.'

2.1.4. Vegetation and land cover

The study area vegetation type, according to the Simplified Acocks Veld Types, varies between tropical bush and savanna types (bushveld) in the lower altitudes and inland tropical forest types at higher altitudes (WR2005b).

The land cover is mostly forest at higher altitudes. Forestry comprises 20.1km^2 of the catchment area (WR2005a). Lower altitudes of the catchment are comprised of dryland agriculture, as well as cultivated land (temporary and commercially irrigated) (WR2005b). The only impoundment in the catchment is the Jan Wassenaar Dam.

2.2. ACTIVITIES WITHIN THE STUDY AREA

The following activities have been identified within the quaternary catchment;

Domestic: The runoff from the mountain is expected to have numerous uses in the surrounding lowland areas, such as supplying the complex of townships, Acornhoek, with freshwater resources.

Agriculture: There are a few small commercial farms in the catchment area, as well as some subsistence farming by communities that work in the area.

Conservancy: The top of the Mariepskop mountain became a military area in 1951 which has led to its preservation and unique floral diversity. The Klaserie river provides high quality water flow to the Olifants river which flows through the Kruger National Park.

Fog-harvesting: Previously, fog-harvesting has been used on Mariepskop to supply water to the South African Air Force personnel manning the Mariepskop radar station (Schutte, 1971). This was the first fog collection installation in South Africa, yielding more than 11 litres of water, per square metre of collecting surface, per day (Schutte, 1971). This project terminated when the personnel manning the Mariepskop radar station found an alternative water supply.

CHAPTER 3: METHODOLOGY

3.1. INTRODUCTION

This chapter documents the data collection process required for the setting up and running of the SWAT model in the B73A quaternary catchment. The output obtained from the model depends on the quality of the input data, highlighting the importance of spending time on data collection and processing. However, as in many mountainous catchment areas, the availability of reliable long-term data within the B73A catchment area is one of the constraints of the study.

3.2. DATASETS

The SWAT model requires the following datasets: a Digital Elevation Model (DEM) of the catchment area, geographical data, climate data and stream flow data. The DEM must be a raster file in Environmental Systems Research Institute (ESRI) grid format. The geographical data refers to land cover and soil data, which should be shape or grid files. The required climate data includes daily precipitation and temperature data, as well as the location of the precipitation and temperature gauges. The climate data should be a text file, in a specific SWAT format.

The SWAT model requires that all data must be in the same projection, although it can be in any projection system. All datasets used in this study were projected to Albers Equal Area, using the D_WGS_1984 datum system.

3.2.1. Geographical data

The DEM (Figure 3.1), as well as the land cover data, was obtained from the ESRI website (http://www.esri.com). The soil data was obtained from the 1990 Surface Water Resources of South Africa Study (WR90). Soil data from the WR90 study is based on the 1989 RBHNR map produced by the Department of Agricultural Engineering, University of Natal.

A field study was carried out in order to perform a ground truth on the land cover data used in the study. The co-ordinates for 27 points were checked to determine if the land cover indicated in the land cover map used was the same as that in the actual B73A quaternary catchment. For each land cover type an example from the B73A quaternary catchment area is shown. These were natural (Figure 3.2), cultivated (Figure 3.3), degraded (Figure 3.4), urban built-up (Figure 3.5), water-bodies (Figure 3.6) or plantation (Figure 3.7). It was verified that the actual land cover on the ground matched the land cover in the map for 85% of the points. The Global Positioning System (GPS) accuracy was recorded as approximately 5 meters for the majority of the sites.

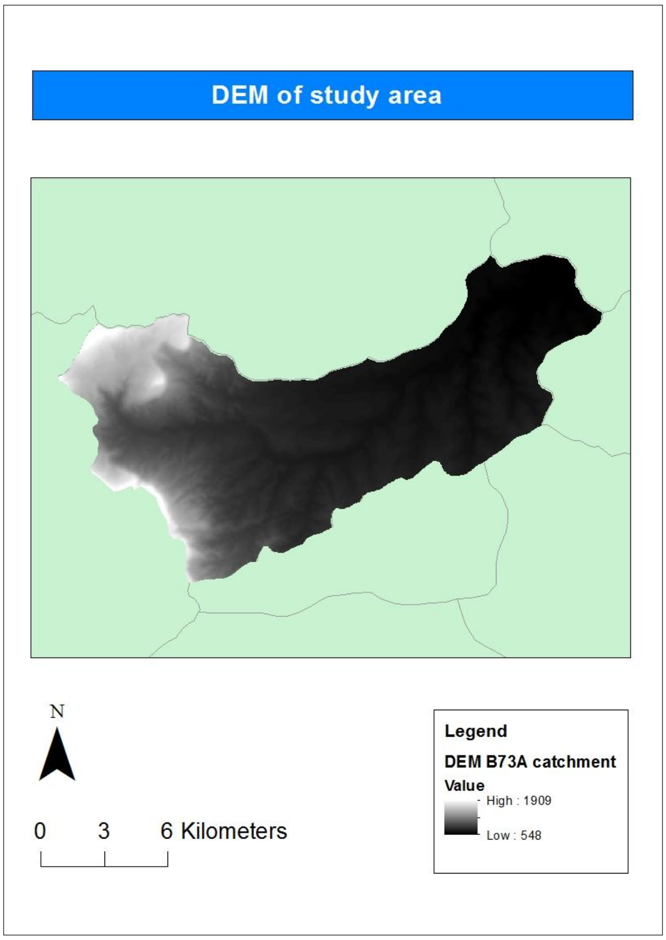


Figure 3.1. The spatial coverage (MASL) of the B73A catchment, as illustrated by the Digital Elevation Model (DEM) of the catchment area.

Figure 3.2. The natural land cover found in the B73A quaternary catchment area. According to the Simplified Acocks Veld Types, the catchment area’s natural land cover varies between tropical bush and savanna types.

Figure 3.3. An example of cultivated land (commercial irrigation) found within the B73A quaternary catchment area.

Figure 3.4. An example of degraded land found in the B73A quaternary catchment area.

Figure 3.5. Urban built-up area located within the B73A quaternary catchment area.

Figure 3.6. An image of a water-body which is located in the B73A quaternary catchment area. Generally in the catchment area, other than the Jan Wassenaar dam, water bodies are small and are not in high quantity.

Figure 3.7. An image of the one of the plantations found in the B73A quaternary catchment area. The plantations are generally a mix of Eucalyptus or pine forests found in the higher altitudes of the catchment.

3.2.2. Climate data

Daily rainfall, temperature, wind speed, relative humidity and solar radiation data was obtained from the National Centre for Environmental Prediction (NCEP), Climate Forecast System Reanalysis (CFSR) website (globalweather.tamu.edu). Data for three weather stations in the vicinity of the study catchment was obtained. They are located at 30.9375 and -24.515, 31.25 and -24.515 and 31.5625 and -24.515. The global weather station located closest to the study catchment is 30.9375 and -24.515 and therefore this station was chosen for use in the study. The location of the global weather station used in the study is shown as a circle in Figure 3.8. DWS has a weather station located just outside the study catchment referred to as the forestry station. This weather station is shown as a square in Figure 3.8. Rainfall records were obtained from this station for use in the study.

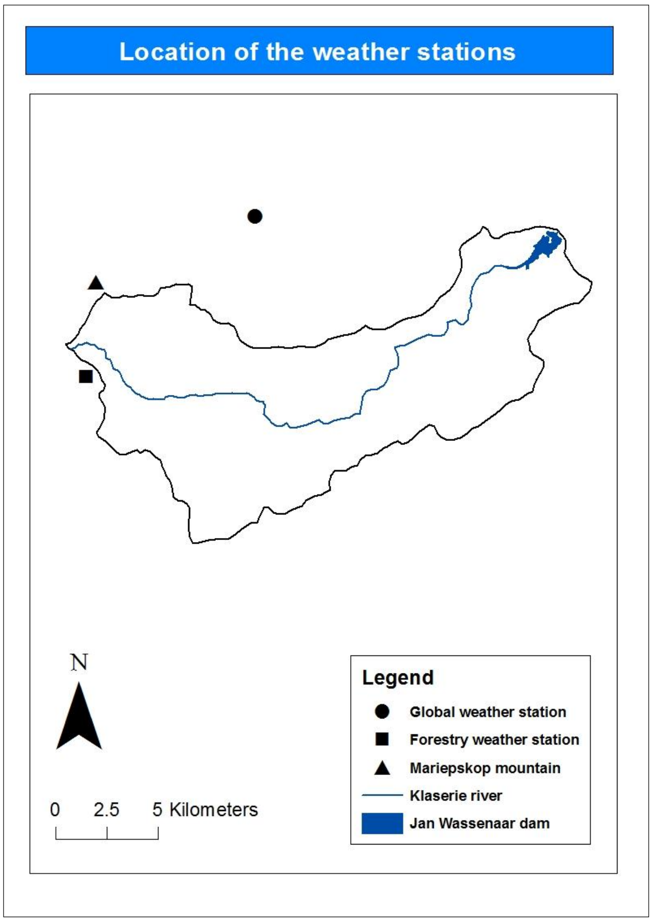


Figure 3.8. Location of the global weather station, shown as a circle, selected for use in the study. The DWS forestry weather station, shown as a square, from which rainfall data was obtained is also shown. Both weather stations are illustrated in relation to the B73A quaternary catchment area.

3.2.3. Stream flow data

For SWAT calibration and validation, daily stream flow data was obtained from the DWS; for stream gauge B7H004. Flow gauge B7H004 is located at -24.5553 and 31.0322 (Figure 3.9). Stream flow data is available from 1962, however there is a substantial amount of data missing, and no data is available for the year 2003. Subsequently, the stream flow data from 1993-1999 will be used for calibration. The data from 2004-2010 will be used for validation purposes. Both periods have no missing data and are therefore seen as the most reliable.

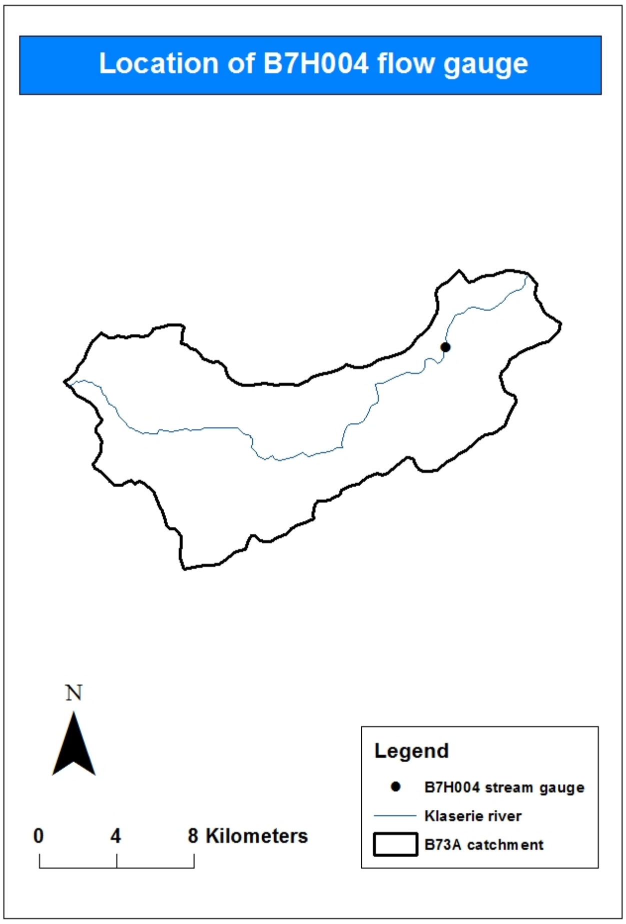


Figure 3.9. Location of stream flow gauge B7H004 in the Klaserie river within the B73A quaternary catchment.

CHAPTER 4: HYDROLOGICAL MODELLING WITH SWAT

4.1. INTRODUCTION

The chosen hydrological model used in this project was the SWAT model. The SWAT model was chosen because of the wide-spread, successful use of the model for a variety of water quantity and quality related purposes in literature (Jayakrishnan *et al*, 2005; Abbaspour *et al*, 2007; Schuol *et al*, 2008; Arnold *et al*, 2012b; Faramarzi *et al*, 2013). The model software is freely available for download on the SWAT website (swat.tamu.edu). There is also a large amount of user support available on this site- including user forums, educational videos and user manuals.

4.2. MODEL SETUP

ArcSWAT version 2012.10_1.11 (2012.10.1.15) was downloaded. Once the ArcSWAT program had been downloaded, a toolbar was added into ArcGIS with the main procedures for the modelling process displayed. This includes the SWAT Project Setup, Watershed Delineator, HRU Analysis, Write Input Tables, Edit SWAT Input and the SWAT Simulation procedures. As each procedure is completed successfully the next step becomes enabled in the program. The toolbar is shown in Figure 4.1.

The “New SWAT Project” button was selected. This opened the “Project Setup” menu (Figure 4.2). The input data, described in the previous chapter, was placed in a “project directory” folder on the desktop computer used for the study. The “Project Directory” button was pressed in the “Project Setup” menu, and the input data folder (the “project directory” folder) on the desktop is selected. This folder will be the only selection made by the user during the setup procedure. It enables the ArcSWAT program to access all the required input data (Winchell *et al*, 2013).

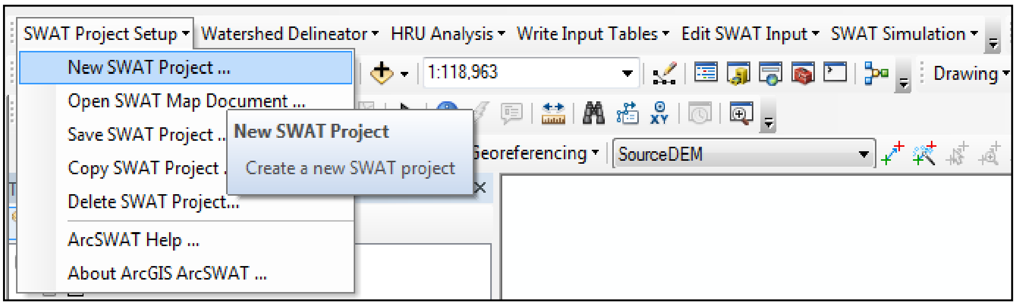
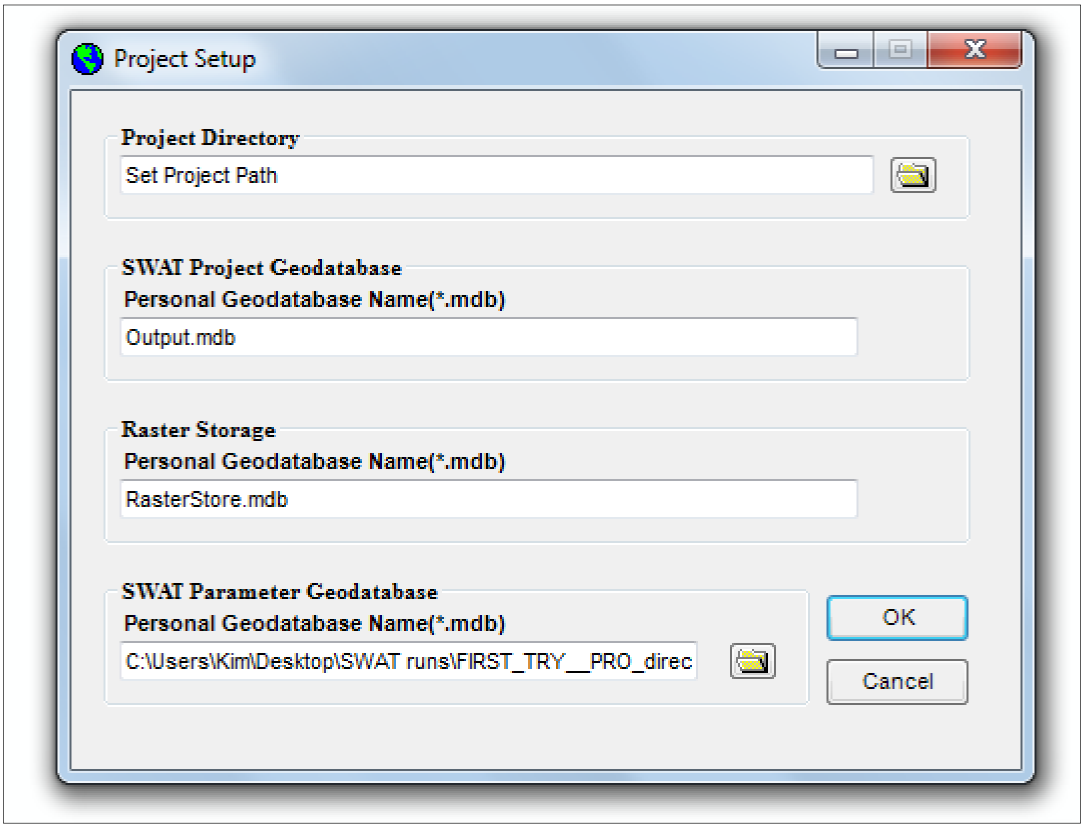


Figure 4.1. The main interface toolbar in the ArcSWAT program.



Project Directory
Set Project Path

SWAT Project Geodatabase
Personal Geodatabase Name(*.mdb)
Output.mdb

Raster Storage
Personal Geodatabase Name(*.mdb)
RasterStore.mdb

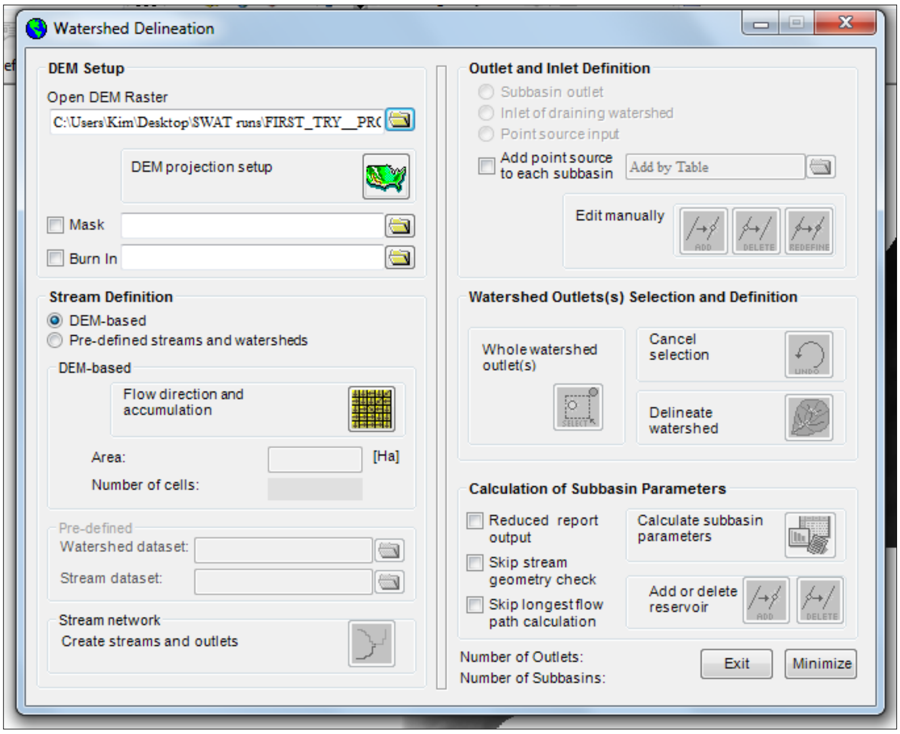
SWAT Parameter Geodatabase
Personal Geodatabase Name(*.mdb)
C:\Users\Kim\Desktop\SWAT runs\FIRST_TRY__PRO_direc

Figure 4.2. The project set up menu located in the SWAT program.

4.2.1. Watershed delineation

The next procedure done in the ArcSWAT program was the watershed delineation. Figure 4.3 shows the submenu found in the ArcSWAT program. The first step was to load the DEM file from the “project directory” folder found on the desktop into the program. The “DEM projection setup” button was pressed. The streams in the watershed then needed to be defined. The program gives two options for the definition of the streams. One option is to input predefined streams and watershed. This option can be used if the location of the streams in the watershed or catchment area are known. The other option, to be used if the exact location of the streams in the catchment is not known, is the DEM- based stream definition. The model assigns stream flow paths based on elevation values from individual cells in the DEM grid. This was the chosen option in this study as the exact location of the streams in the catchment area was not known.

The program generates sub-basin outlets. However, these outlets can be modified. This is useful if there is a known location of a stream flow gauge in the catchment area. For later calibration purposes, the position of the stream flow-gauging station B7H004 was added manually during the model setup process, by pressing the “Add” button under the “Outlet and Inlet Definition” area in the watershed delineation submenu.


Open DEM Raster: C:\Users\Kim\Desktop\SWAT runs\FIRST_TRY__PR(

Stream Definition: ● DEM-based ○ Pre-defined streams and watersheds

Figure 4.3. The watershed delineation sub menu used in the ArcSWAT program to delineate the B73A quaternary catchment area.

To define the overall area that will be modelled, a whole watershed outlet was selected. The watershed was then successfully delineated, which refers to the process of creating sub-basins within the whole watershed area. The threshold size of these sub-basins can be specified by the user. The smaller the area, the more detailed the drainage network will be. In this study, an area of 2.806 hectares was specified.

The ArcSWAT program generates a report detailing the statistical summary and distribution of discrete land surface elevations in the sub-watershed and watershed. The delineated watershed, as well as the stream network created by the ArcSWAT program during the stream definition process, is shown in Figure 4.4.

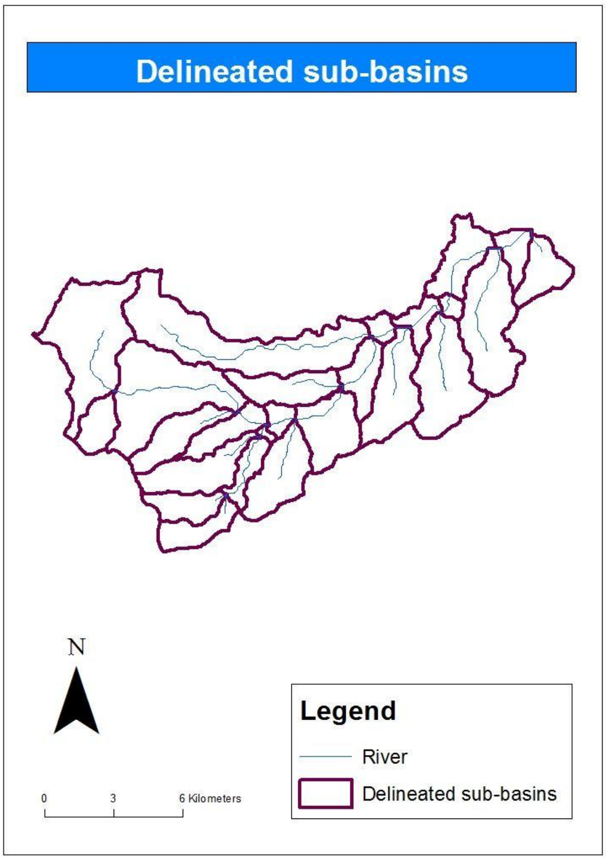
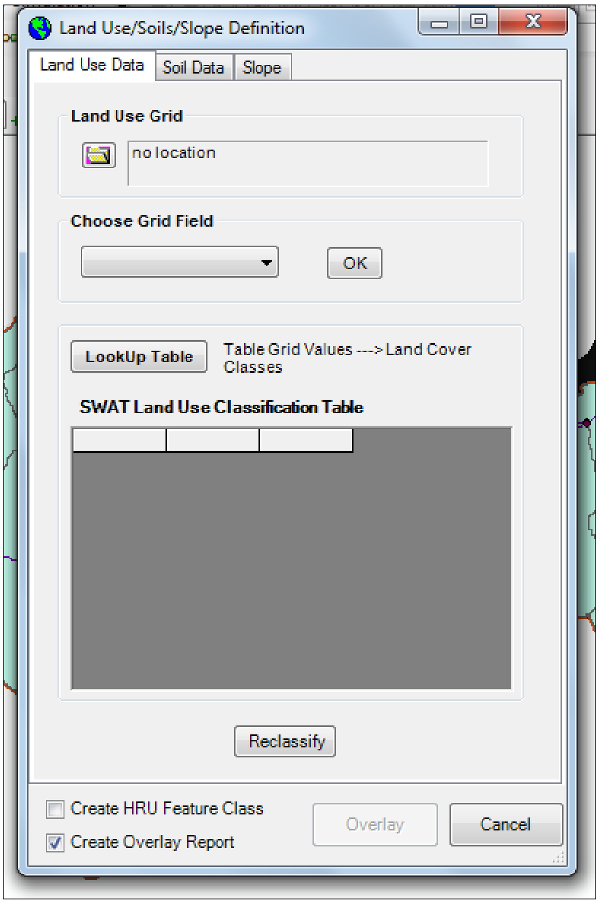


Figure 4.4. The delineated sub-basins (shown in purple) that were generated during the watershed delineation process of the B73A quaternary catchment area. The stream network that was created during the stream definition process is also shown (shown in blue).

4.2.2. Soil, land use, slope definition and overlay

The definition and overlay process divides the sub-basins into areas of similar soil, land use and slope. These areas are termed hydrological response units (HRUs). Figure 4.5 shows the overlay menu. This is where the user starts to make choices based on information of their specific catchment area.



no location

☐ Create HRU Feature Class
☑ Create Overlay Report

Figure 4.5. The overlay menu found in the SWAT program.

Land use and soil data was required for the overlay process. The ArcSWAT program contains databases with SWAT land use and soil classes, with respective default properties assigned to them. Since the model originates and is widely used in the USA, these land use and soil classes are those that are found in the USA. An option is provided which allows users to manually add new classes to the SWAT database. The user can then add classes' specific to their area of interest. This is useful for users that are modelling catchments which are not in the USA.

The land cover shape file for the B73A catchment was obtained from the South African National Biodiversity Institute (SANBI) (2009). For this study, the different land covers in the shape file were reclassified according to the available SWAT land cover classes found in the SWAT database (Table 5.1). It is recommended, especially for land use change studies which should reflect the land use of an area in detail, that the SWAT database be updated with data from the particular catchment area (Dabrowski, 2013; Winchell *et al*, 2013). However, many of the land cover and plant growth types included in the SWAT database are common to those occurring in South Africa. For this study it was decided to use land cover types that were already available in the SWAT database for simplicity. Figure 4.6 shows the SWAT land use classes found in the B73A catchment.

Natural Veld was classified as the SWAT land cover class Pastures (PAST). The SWAT land class Agricultural Land - Generic (AGRL) was chosen instead of the Agricultural Land - Row Crops (AGRR) class. The cultivation in the catchment is mainly comprised of subsistence dryland farming (0.00143 hectares), with a small area (0.000361 hectares) of commercial irrigation cultivation (Figure 4.7). Degraded land was classified as the SWAT land cover class Disturbed Lands (RNGE). Urban built-up areas were classified as Residential (URBN). Waterbodies were classified as Water (WATR), which refers to open water. The plantations were specified to be Evergreen Forests (FRSE) as the plantations are known to be either Eucalyptus or pine forests, which are both evergreen. Mines were classified as Industrial areas (UIDU).

Table 4.1 Land use conversion from SANBI land cover classes to ArcSWAT database classes.

SANBI land cover classes	SWAT land cover classes
Natural	PAST
Cultivation	AGRL
Degraded	RNGE
Urban Built-Up	URBN
Waterbodies	WATR
Plantations	FRSE
Mines	UIDU

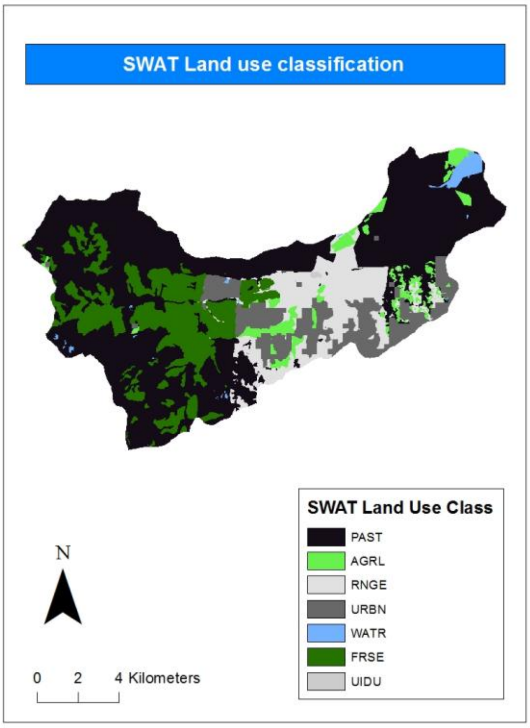


Figure 4.6. The SWAT land use classification for the B73A quaternary catchment area. Illustrated are the resulting land use classes after converting SANBI land cover types to the ArcSWAT land use classes found in the ArcSWAT database.

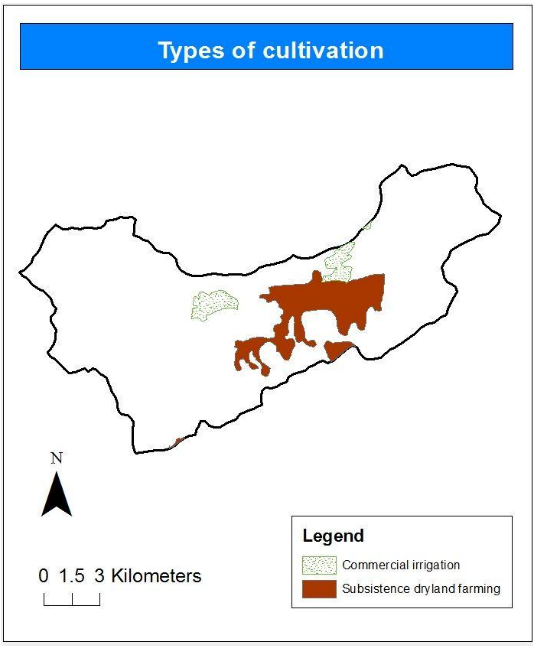


Figure 4.7. Types of cultivation found in the B73A quaternary catchment area. Cultivation was separated into commercial irrigation and subsistence dryland farming.

Soil is an important factor in determining the amount of run-off in a catchment. Different soil properties within a catchment or between catchments can have a major effect on the rates of, and lags in, hydrological processes (Schulze, 1989). The different soil classes were defined in the user soil database in the SWAT model. The soil classes used were based on the land type survey done by the Agricultural Research Institute: Institute of Soil, Water and Climate (ARC). The different soil classes are referred to as land types by the ARC.

The following information for each soil class is required in the user soil database. Firstly, soil component parameters needed are: **NLAYERS** which is the number of layers found in the soil class. **HYDGRP**, or soil hydrologic group, is based on the infiltration characteristics of the soils. The **SOL_ZMX** refers to the maximum rooting depth of the soil profile.

For each layer found within the particular soil class, the following parameters are required: **SOL_Z**, the depth from the soil surface to the bottom of the layer. **SOL_BD** refers to the moist bulk density. **SOL_AWC**, the available water capacity of the soil layer must be specified. **SOL_CBN** is the saturated hydraulic conductivity of the soil layer. **SOL_K** referring to the organic carbon content needs to be specified. The clay, silt, sand, rock fragment content is required. The moist soil albedo, **SOL_ALB**, is required. **USLE_K** refers to the USLE equation soil erodibility (K) factor.

The soil definition was done by using soil profile data for the dominant soil series in the land type. The soil series adopted for each land type are shown in Table 4.2. As some of the land types found within the catchment had the same dominant soil series, these land types were subsequently merged. Figure 4.8 is the resulting dominant soil series found in the catchment and used for the study. The required information about each soil class, specified in the previous paragraphs, was then found for the dominant soil series in each land type. The information was obtained through the Land Type Inventory accessed on the ARC website (www.agis.agric.za), as well as through the soil classification system for South Africa (“Red Book”) (MacVicar *et al*, 1977). Some of the soil information required by the model can only be obtained by complicated, on site measurements. Therefore parameters, such as percentage of rocks and soil albedo, were estimated from other parameters as described by Schulze (2007), as well as by visits to the study area.

Table 4.2. Dominant soil series adopted for each land type found within the B73A quaternary catchment.

Land type	Dominant soil series
Ab40	Hu17
Ab32	Hu17
Hb1	Fw12
Ib193	Rock
Ib161	Rock
Ab59	Hu17; Hu18
Ab41	Hu17; Hu27; Hu28
Fb182	Gs14; Gs15; Gs18
Fb181	Gs14; Gs15; Gs18

The last step before the overlay operation can be performed is to define slope classes that will be used to establish the hydrological response units (HRU's). The SWAT user manual states that this is important if sub-basins are known to have a wide range of slopes occurring within them (Winchell *et al*, 2013). For the B73A catchment four slope classes were chosen. The catchment has a varied range of slopes observed from visiting the area, as well as studying the land type inventories found within the catchment (www.agis.agric.za).

After the overlay process was completed, the program generated a report which details the distribution of the land use, soil and slope classes in the watershed.

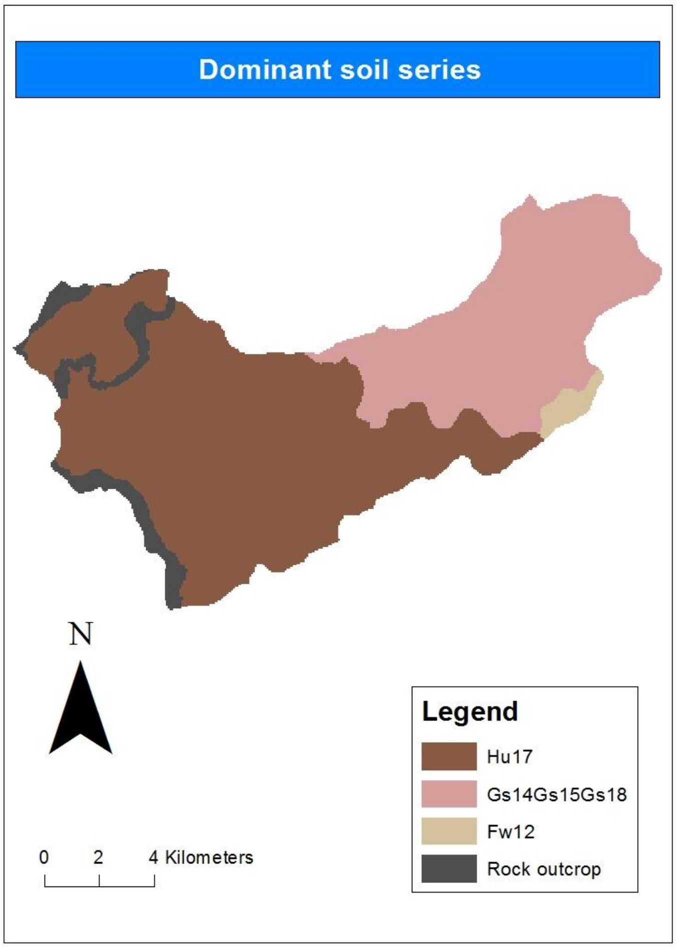
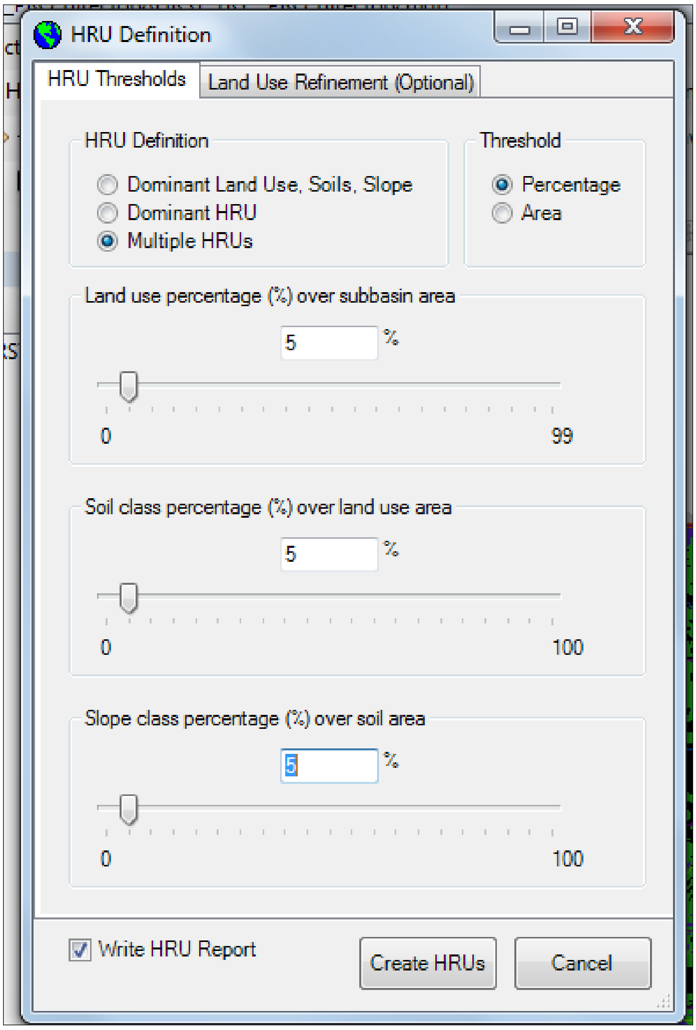


Figure 4.8. The dominant soil series found in the B73A quaternary catchment area.

4.2.3. Hydrological Response Unit (HRU) definition

Following the importation and overlay of the land use, soil and slope data layers into the ArcSWAT program, the HRU's must be determined. The HRU definition menu is shown in figure 4.9. HRU's refer to homogeneous areas that represent unique combinations of soil, land use and slope. A single HRU can be assigned to each sub-watershed or multiple HRU's. In the case of a single HRU being selected for each sub-watershed, the program will assign the dominant land use category, soil type and slope class to determine the HRU. Multiple HRU's are determined by sensitivities for the land use, soil and slope data specified by the user. For this study, multiple HRU's were selected. The sensitivity, or threshold, value used was 5% for land use, soil and slope class. This refers to the percentage of the land use, soil or slope class that covers the sub-basin area under which that class is considered negligible and is excluded from the analysis. This value is determined by the particular goals of the modeller. For this study the amount of detail required is quite high. This is due to the size of the catchment, as well as the fact that the catchment is mountainous which means that there will be many microclimates found in the area. The threshold value was therefore made relatively low.



HRU Definition
○ Dominant Land Use, Soils, Slope
○ Dominant HRU
● Multiple HRUs

Threshold
● Percentage
○ Area

Land use percentage (%) over subbasin area
5 %
0 99

Soil class percentage (%) over land use area
5 %
0 100

Slope class percentage (%) over soil area
5 %
0 100

☑ Write HRU Report

Figure 4.9. The Hydrologic Response Unit (HRU) definition menu in the ArcSWAT program. Multiple HRU's were selected for the study. The sensitivity value used for land use, soil and slope classes was 5%.

4.2.4. Weather data definition

The next step was to load the weather data into the model. The weather data definition menu is shown in figure 4.10. The first tab was the weather generator data tab. This is an important process if the weather data used has gaps in it. As the weather data used for this study was from the global weather data site, it did not have any missing records that needed to be filled by the weather generator data. The WGEN_user option was selected for this study instead of any weather generator options.

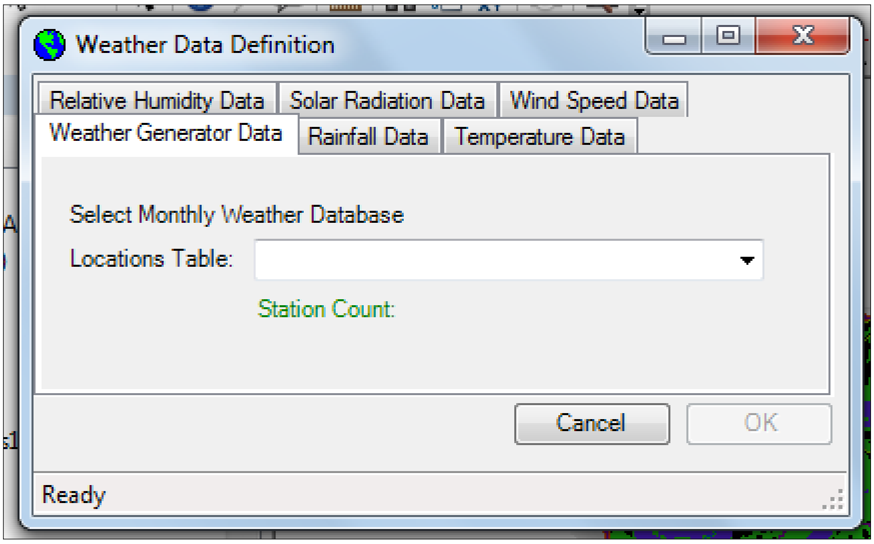
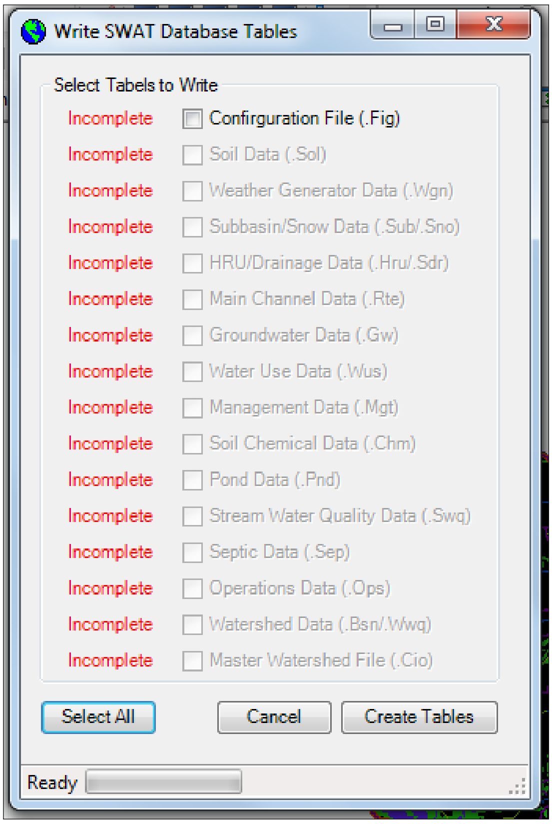


Figure 4.10. Weather data definition menu in the ArcSWAT program.

The next five tabs in the weather data definition menu were used to add the weather data into the ArcSWAT program. This was done by successively specifying the rainfall, temperature, wind speed, solar radiation and wind speed gauges for the B73A quaternary catchment. The "Location Table" of each gauge is required. These locations were placed into the "project directory" folder on the desktop and were specified during the weather data definition process for each required weather variable in the ArcSWAT program.

4.2.5. Write input tables

The ArcSWAT program built database files that contained information needed to generate default input for the running of the SWAT model (Arnold *et al*, 1998). The "Select All" button was pressed, and then "Create Tables" after which the ArcSWAT program created and populated SWAT input tables with default values. The indication that the process was complete was the tick in the box and the "completed" next to each SWAT table name.



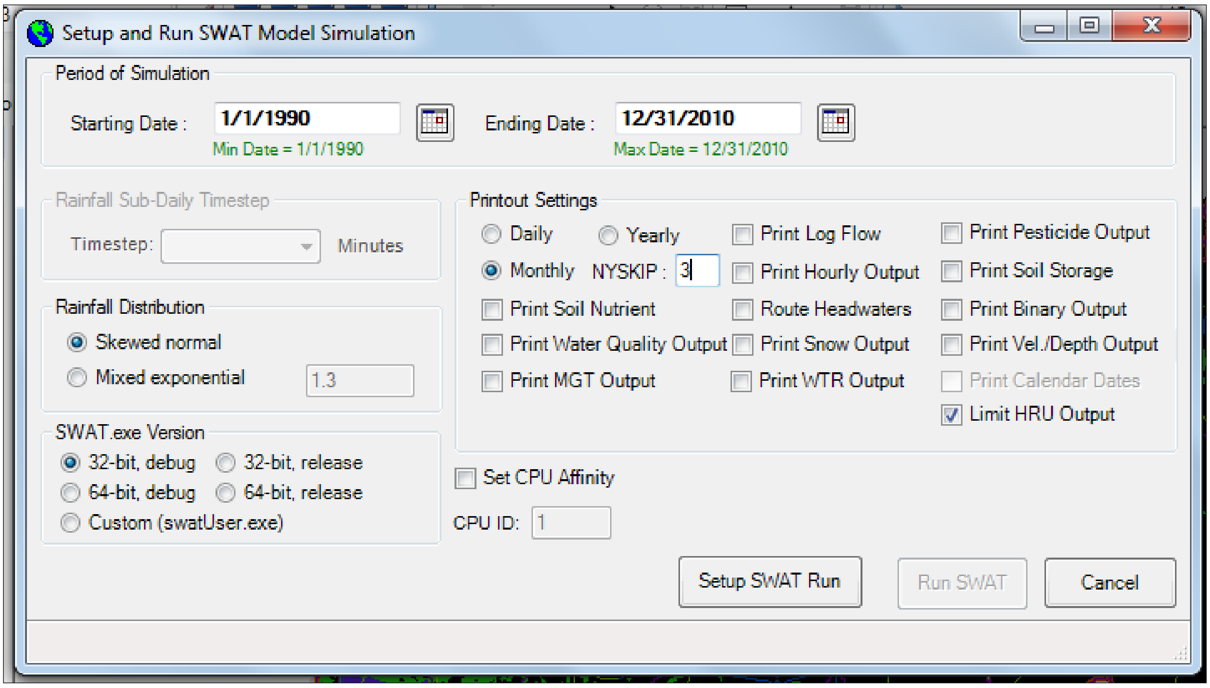
Incomplete ☐ Confirguration File (.Fig)
Incomplete ☐ Soil Data (.Sol)
Incomplete ☐ Weather Generator Data (.Wgn)
Incomplete ☐ Subbasin/Snow Data (.Sub/.Sno)
Incomplete ☐ HRU/Drainage Data (.Hru/.Sdr)
Incomplete ☐ Main Channel Data (.Rte)
Incomplete ☐ Groundwater Data (.Gw)
Incomplete ☐ Water Use Data (.Wus)
Incomplete ☐ Management Data (.Mgt)
Incomplete ☐ Soil Chemical Data (.Chm)
Incomplete ☐ Pond Data (.Pnd)
Incomplete ☐ Stream Water Quality Data (.Swq)
Incomplete ☐ Septic Data (.Sep)
Incomplete ☐ Operations Data (.Ops)
Incomplete ☐ Watershed Data (.Bsn/.Wwq)
Incomplete ☐ Master Watershed File (.Cio)

Figure 4.11. Write input table menu in the ArcSWAT program which enabled the ArcSWAT program to write all input tables used in the running of the SWAT model.

4.3. RUNNING THE SWAT MODEL

Before the SWAT model was run there was an option to edit the ArcSWAT input. This could have been done under the ‘Edit SWAT input’ tab. This is useful if, for example, the user wants to use the model for potential scenarios of land cover change or climate change. For this project, no input was edited. The model output with these known conditions will be compared to simulated flow records of the same conditions, to assess the ability of the SWAT hydrological model to predict stream flow in the B73A quaternary catchment.

The setup menu for the running of the SWAT model is shown in figure 4.12. Before the model could be run, the period of simulation needed to be specified. For this study, the period of simulation was from 1/01/1990 to 12/31/2010 with monthly time intervals. The “Printout Settings” were specified as “Monthly” frequency. The rainfall distribution was left as “Skewed Normal”. A period of three years warm-up was specified by the monthly NYSKIP (Figure 4.12).


Setup and Run SWAT Model Simulation

Period of Simulation
Starting Date : 1/1/1990 Min Date = 1/1/1990
Ending Date : 12/31/2010 Max Date = 12/31/2010

Rainfall Sub-Daily Timestep
Timestep: Minutes

Rainfall Distribution
● Skewed normal
○ Mixed exponential 1.3

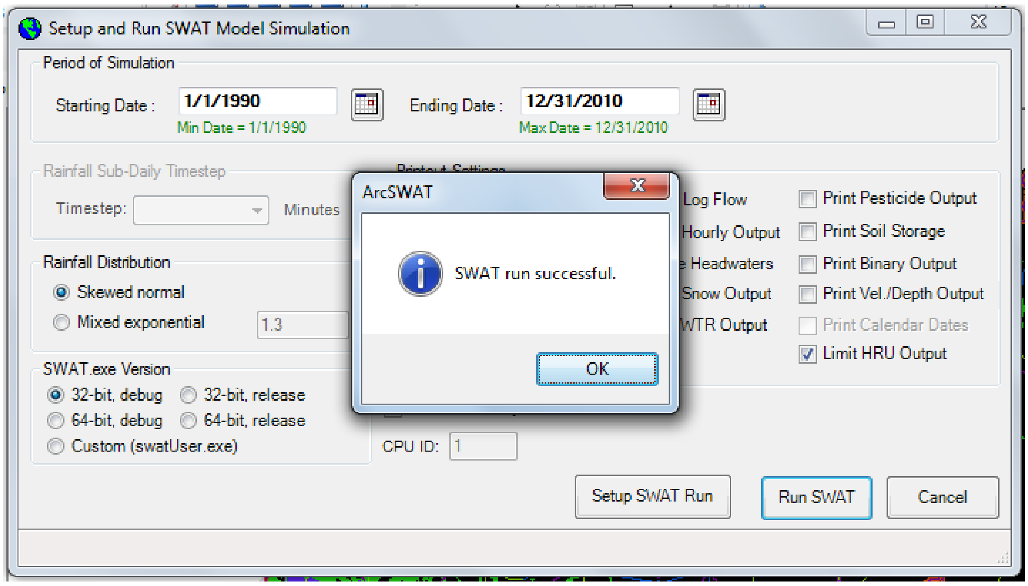
SWAT.exe Version
● 32-bit, debug ○ 32-bit, release
○ 64-bit, debug ○ 64-bit, release
○ Custom (swatUser.exe)

Printout Settings
○ Daily ○ Yearly ☐ Print Log Flow ☐ Print Pesticide Output
● Monthly NYSKIP : 3 ☐ Print Hourly Output ☐ Print Soil Storage
☐ Print Soil Nutrient ☐ Route Headwaters ☐ Print Binary Output
☐ Print Water Quality Output ☐ Print Snow Output ☐ Print Vel./Depth Output
☐ Print MGT Output ☐ Print WTR Output ☐ Print Calendar Dates
☑ Limit HRU Output

☐ Set CPU Affinity
CPU ID: 1

Figure 4.12. The setup menu for the process of running the SWAT model in the ArcSWAT program. The period of simulation was from 1/01/1990 to 12/31/2010 with monthly time intervals. Three years were specified as the warmup period (NYSKIP).

The “Setup SWAT Run” button was initiated. After the model had finished the SWAT setup, the “Run SWAT” button was enabled and the model could be run. The model executed each year individually and indicated when it had simulated the period specified successfully (Figure 4.13).


Setup and Run SWAT Model Simulation

Period of Simulation
Starting Date : 1/1/1990 Min Date = 1/1/1990
Ending Date : 12/31/2010 Max Date = 12/31/2010

Rainfall Sub-Daily Timestep
Timestep: Minutes

Rainfall Distribution
● Skewed normal
○ Mixed exponential 1.3

SWAT.exe Version
● 32-bit, debug ○ 32-bit, release
○ 64-bit, debug ○ 64-bit, release
○ Custom (swatUser.exe)

Log Flow ☐ Print Pesticide Output
Hourly Output ☐ Print Soil Storage
Headwaters ☐ Print Binary Output
Snow Output ☐ Print Vel./Depth Output
WTR Output ☐ Print Calendar Dates
☑ Limit HRU Output

CPU ID: 1

ArcSWAT
SWAT run successful.

Figure 4.13. The completion of a successful SWAT simulation.

CHAPTER 5: CALIBRATION AND VALIDATION

5.1. THE CONCEPT OF CALIBRATION AND VALIDATION

Calibration is described by Arnold *et al* (2012b) as '…an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty.' Validation is described as the process of '…demonstrating that a given site-specific model is capable of making sufficiently accurate simulations, although sufficiently accurate results can vary based on project goals.' (Arnold *et al*, 2012b).

5.2. EVALUATION CRITERIA FOR MODEL PERFORMANCE

For evaluation of model performance, Moriasi *et al* (2007) describe model evaluation guidelines for quantification of accuracy in watershed modelling. This paper was generally followed as the standard for assessing our model performance, as well as a few other accredited publications in literature (Saleh *et al*, 2000; Van Liew *et al*, 2007). These other publications were used by Moriasi *et al* (2007) in their guidelines. It is suggested that both graphical techniques and quantitative statistical analysis should be used to compare the measured or observed data to the simulated data (Moriasi *et al*, 2007). In this project graphical techniques were used, as well as the following three quantitative statistics: the coefficient of determination (R^2), Nash-Sutcliffe (1970) Efficiency (NSE) and Percent BIAS (PBIAS).

The coefficient of determination (R^2) describes the degree of collinearity between simulated and measured data (Moriasi *et al*, 2007). R^2 ranges from 0 to 1, with higher values indicating less error variance. Values of R^2 greater than 0.5 are considered to be acceptable (Moriasi *et al*, 2007).

NSE is recommended and widely used in literature (ASCE, 1993; Moriasi *et al*, 2007), therefore there is a lot of reported values for use as evaluation guidelines. NSE, in a simplified explanation by Moriasi *et al* (2007), is an '…indication of how well the plot of observed versus simulated data fits the 1:1 line.'. NSE is computed as shown in the following equation:

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

where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

The range of NSE is between $-\infty$ and 1.0 (1 inclusive), with NSE = 1.0 being the optimal value. Moriasi *et al* (2007) suggest that in general model simulation can be judged as satisfactory if NSE > 0.50. Values ≤ 0.0 indicate that the mean observed value is a better predictor than the simulated value and therefore is unacceptable model performance.

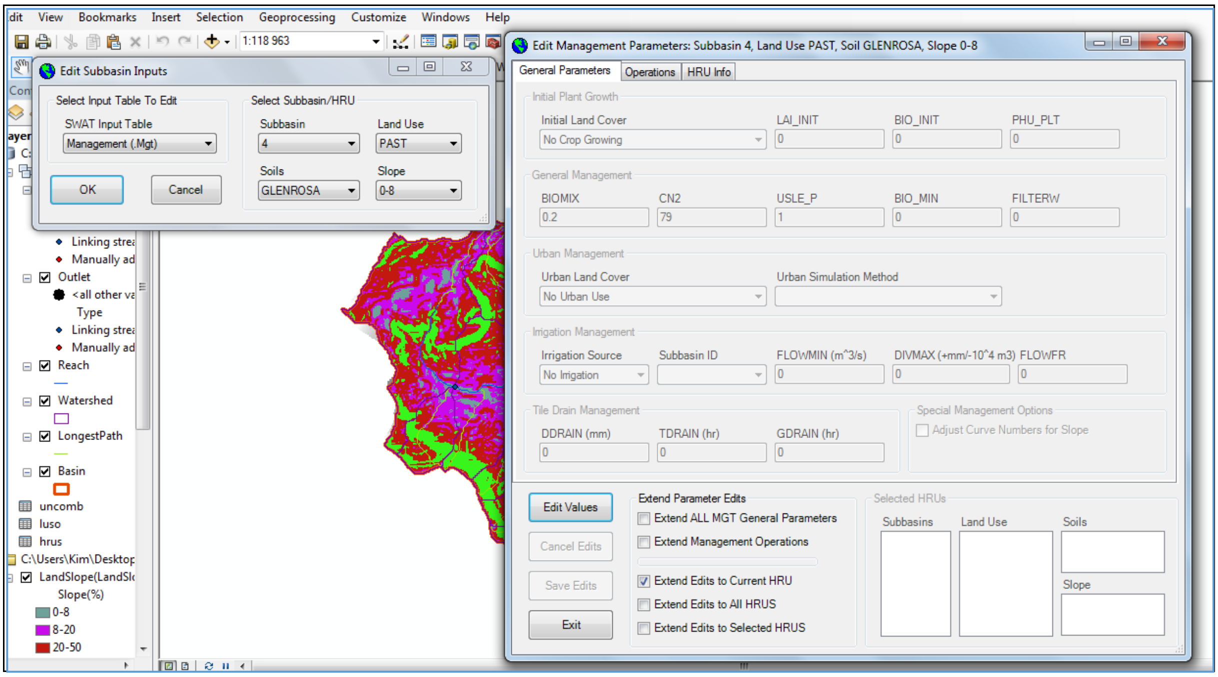
Another quantitative statistical measure used to assess the agreement between simulated and observed data will be the PBIAS of the two sets of data. The PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta *et al*, 1999). Performance ratings state that if a value of <10% to <15% is achieved for PBIAS, this is a good performance (Moriasi *et al*, 2007; Van Liew *et al*, 2007). A PBIAS value >25% is considered unsatisfactory (Van Liew *et al*, 2007).

5.3. MANUAL CALIBRATION

After running the model and obtaining the initial results, manual calibration was done on certain default parameters, namely the runoff curve number (CN2) and the base flow recession constant (ALPHA_BF). Initially to calibrate our model we followed the ‘Basic water balance and total flow calibration’ guidelines given in the Soil and Water Assessment Tool User’s Manual: Version 2000 (Neitsch *et al*, 2002). This is a manual process of a sort of trial-and-error approach to obtain parameter values that better represent the modelled monthly total flow from the catchment (Arnold *et al*, 2012a).

The value of CN2 was adjusted according to the “Tables of runoff curve number values” from the Urban Hydrology for Small Watersheds, USDA technical report (USDA, 1986). The value of ALPHA_BF was adjusted according to expert opinions on the SWAT user group, as well as from personal communication and use of the documentation on the SWAT website (SWAT user group; Abbaspour, User group; Dabrowski, 2013).

Adjustments to the CN2 parameter are made in the Management (.Mgt) SWAT Input Table found in the Sub-basin Data, under the Edit SWAT Input tab (Figure 5.1).



Edit Subbasin Inputs

Select Input Table To Edit

SWAT Input Table: Management (.Mgt)

Select Subbasin/HRU

Subbasin: 4

Land Use: PAST

Soils: GLENROSA

Slope: 0-8

Edit Management Parameters: Subbasin 4, Land Use PAST, Soil GLENROSA, Slope 0-8

Initial Plant Growth

Initial Land Cover: No Crop Growing

LAI_INIT: 0

BIO_INIT: 0

PHU_PLT: 0

General Management

BIOMIX: 0.2

CN2: 79

USLE_P: 1

BIO_MIN: 0

FILTERW: 0

Urban Management

Urban Land Cover: No Urban Use

Urban Simulation Method:

Irrigation Management

Irrigation Source: No Irrigation

Subbasin ID:

FLOWMIN (m^3/s): 0

DIVMAX (+mm/-10^4 m3): 0

FLOWFR: 0

Tile Drain Management

DDRAIN (mm): 0

TDRAIN (hr): 0

GDRAIN (hr): 0

Special Management Options

☐ Adjust Curve Numbers for Slope

Extend Parameter Edits

☐ Extend ALL MGT General Parameters

☐ Extend Management Operations

☑ Extend Edits to Current HRU

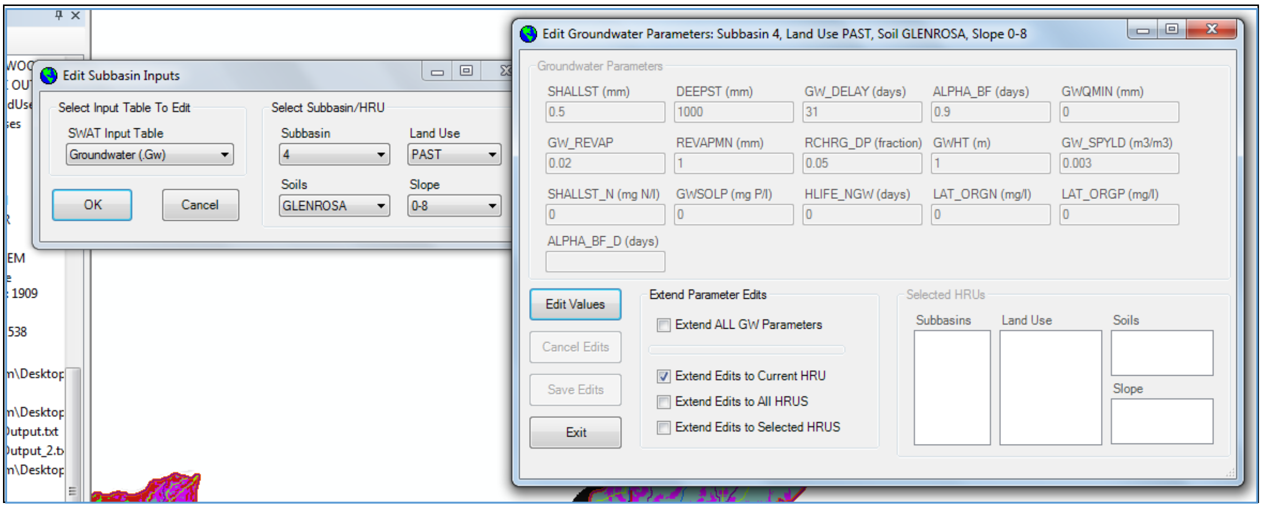
☐ Extend Edits to All HRUS

☐ Extend Edits to Selected HRUS

Figure 5.1. The 'Edit Subbasin Inputs and the Edit Management Parameters' menu.

Adjustments to the base flow recession constant (ALPHA_BF) are conducted in the Groundwater (.Gw) SWAT Input Table found in the Sub-basin Data, under the Edit SWAT Input tab (Figure 5.2).

Calibration attempted by manually changing the values of the parameter above did not give acceptable results. Generally, manual calibration is also known to be time-consuming and frustrating (Gupta *et al*, 1999). The SWAT model needed to be able to sufficiently predict the runoff from the B73A study catchment, so another method to calibrate the model needed to be adopted, to fine tune the model in a way. The SWAT 2012 program does not include in the interface a tool to calibrate the model as earlier versions did (auto-calibration tool). To calibrate the model, SWAT-CUP 2012 program was downloaded from the SWAT website (www.swat.tamu.edu).



SWAT Input Table: Groundwater (.Gw)
Subbasin: 4
Land Use: PAST
Soils: GLENROSA
Slope: 0-8

SHALLST (mm): 0.5
DEEPST (mm): 1000
GW_DELAY (days): 31
ALPHA_BF (days): 0.9
GWQMIN (mm): 0
GW_REVAP: 0.02
REVAPMN (mm): 1
RCHRG_DP (fraction): 0.05
GWHT (m): 1
GW_SPYLD (m3/m3): 0.003
SHALLST_N (mg N/l): 0
GWSOLP (mg P/l): 0
HLIFE_NGW (days): 0
LAT_ORGN (mg/l): 0
LAT_ORGP (mg/l): 0
ALPHA_BF_D (days):

☐ Extend ALL GW Parameters
☑ Extend Edits to Current HRU
☐ Extend Edits to All HRUS
☐ Extend Edits to Selected HRUS

Figure 5.2. The Edit Subbasin Inputs and the Edit Groundwater Parameters menu. The Edit Groundwater Parameters menu is used to modify the groundwater (.Gw) input file.

5.4. CALIBRATION AND VALIDATION USING SUFI-2 IN SWAT-CUP

SWAT-CUP links various procedures, including Sequential Uncertainty Fitting (SUFI-2), to SWAT and enables sensitivity analysis, calibration, validation and uncertainty analysis of SWAT models (Abbaspour, 2014).

For the calibration of the SWAT model in this project, SUFI-2 was chosen. The SUFI-2 program is semi-automated, meaning that some steps during the calibration process the user needs to do manually (Abbaspour, 2014). This requires that the user becomes more familiar with the parameters used in the SWAT model, as well as with the hydrological characteristics within the particular watershed being modelled. The program incorporates both sensitivity and uncertainty analysis.

5.4.1. Parameters

In this study, the parameters that were used for the calibration process were selected and adjusted by expert opinion in literature (Arnold *et al*, 2012b) and by examination of sensitivity analysis results. Following is a short description of the parameters chosen for calibration in the SUFI-2 program. They can be separated into surface response, subsurface response and basin parameters:

Surface response parameters

CN2

The runoff curve number (CN2). In the SWAT model, this parameter is the initial SCS runoff curve number (CN2). The runoff curve number is an empirical parameter used to predict direct runoff and infiltration from rainfall excess. The parameter reflects soil permeability, land use and antecedent soil water as it is a function of these conditions (Neitsch *et al*, 2002).

ESCO

The soil evaporation compensation coefficient, ESCO, is one of the SWAT input variables that are used in soil evaporation calculations (Neitsch *et al*, 2011). Arnold *et al*. (2012a) explain the incorporation of this coefficient as follows '…the incorporation of this coefficient allows the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks.' As the value for ESCO is reduced, the model extracts more of the evaporative demand from lower levels (Arnold *et al*, 2012a).

SOL_AWC

Available water capacity of the soil layer (mm H_20/mm soil). The plant available water is calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity (Neitsch *et al*, 2011).

Basin response parameter

SURLAG

Surface runoff lag coefficient. SWAT has incorporated a feature that controls the fraction of the total available water that is allowed to enter the reach on any one day (Arnold *et al*, 2012a). This is in essence a surface runoff storage feature which lags a portion of the surface runoff release to the main channel (Arnold *et al*, 2012a).

Subsurface response parameters

ALPHA_BF

Base flow recession constant. This constant is a direct index of groundwater flow response to changes in recharge (Arnold *et al*, 2012a).

GW_REVAP

Groundwater "revap" coefficient. As stated in the SWAT input/output documentation (Arnold *et al*, 2012a), 'water may move from the shallow aquifer into the overlying unsaturated zone. As GW_REVAP approaches 0, movement of water from the shallow aquifer to the root zone is restricted. As GW_REVAP approaches 1, the rate of transfer from the shallow aquifer to the root zone approaches the rate of potential evapotranspiration.'

GWQMN

Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_20).

GW_DELAY

Groundwater delay time (in days). The lag between the time from which water moves from the soil profile into the shallow aquifer (Arnold *et al*, 2012a). This time is dependent on the depth of the water table, as well as on hydraulic properties of the geologic formations in the vadose and groundwater zones (Arnold *et al*, 2012a).

REVAPMN

Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H_20).

5.4.2. Global sensitivity analysis

The first step involved in the calibration and validation process is to perform a sensitivity analysis. Sensitivity analysis can be defined as the process of determining the rate of change in model output with respect to changes in model input (parameters) (Arnold *et al*, 2012b). Two kinds of sensitivity analysis are performed: local (one-at-a-time) and global analysis. In this study we examined the results of the global sensitivity analysis performed in SUFI-2. The sensitivity of one parameter often depends on the value of other related parameters (Arnold *et al*, 2012b), which is a problem with local sensitivity analysis. Global analysis requires a large number of simulations (Arnold *et al*, 2012b) which can also be a problem. However with this study, the number of simulations used for calibration was 500, which will hopefully be large enough to get accurate results for a global sensitivity analysis.

5.4.3. Calibration

Calibration is model testing with known measured output, and adjusting parameters which will result in a more accurate representation of the system being modelled. Arnold *et al*. (2012b) state that 'calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty in the model'. Gupta *et al*. (1999) state that the usefulness of a model depends on how well the model is calibrated, highlighting the importance of this process in modelling a catchment. The calibration period was from years 1993-1998. The program was simulated 500 times for two iterations.

Parameters are usually carefully selected and adjusted either by expert judgement or by sensitivity analysis (Arnold *et al*, 2012b). In this project, parameters were adjusted both by what were commonly done in previous studies (Arnold *et al*, 2012b; USDA, 1986) and by the global sensitivity analysis conducted in SUFI-2. Table 5.1 shows the parameters used in calibration for surface runoff and base flow in selected SWAT watershed studies (Arnold *et al*, 2012b).

Table 5.1.Calibration parameters used in selected SWAT watershed studies to calibrate surface runoff and baseflow processes. Numbers in parentheses are the number of times the parameter was used in calibration (Source: Adapted from Arnold *et al*, 2012b).

Process	**Input Parameters**					
Surface runoff	CN2 (36)	AWC (28)	ESCO (23)	EPCO (10)	SURLAG (22)	OV_N (8)
Baseflow	GW_ALPHA (28)	GW_REVAP (18)	GW_DELAP (21)	GW_QWN (12)	REVAPMN (13)	RCHARG_DP (14)

During the set-up of the SUFI-2 program, the user inputs an 'objective function', which will be used as the statistical measure describing the calibrated and validated results. For this study the objective function was chosen to be the NSE. Therefore for our objective function type NSE was used, where NSE>0.5.

The parameters that were used for calibration in SWAT-CUP, as well as their initial ranges and the way they were adjusted in SWAT-CUP are shown in Table 5.2. The type of change applied to a parameter can be explained as follows, according to the "Parameterization in SWAT-CUP" in the SWAT-CUP user manual (Abbaspour, 2014):

> Relative (r_) means the existing parameter value is multiplied by (1+ a given value).
> Replace (v_) means the existing parameter value is to be replaced by the given value.

Table 5.2. The initial SWAT parameter ranges put into the SWAT-CUP program SUFI-2 for the first iteration during calibration. The method of adjusting the parameters during the calibration process using the SUFI-2 program is shown. Relative means the existing parameter value is multiplied by (1+ a given value). Replace means the existing parameter value is to be replaced by the given value.

Parameter Name	**Description**	**Range**		**Change**
		Min	**Max**	
Surface response				
CN2.mgt	SCS runoff curve number	35	98	Replace
ESCO.hru	Soil evaporation compensation factor	0	1.00	Replace
SOL_AWC.sol	Available water capacity of the soil layer (mm H_2O/mm soil)	0	1.00	Relative
Subsurface response				
ALPHA_BF.gw	Baseflow recession constant	0	1.00	Replace
GW_DELAY.gw	Groundwater delay (days)	0	500	Replace
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0	5000	Replace
GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.2	Replace
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	0	500	Replace
Basin response				
SURLAG.bsn	Surface runoff lags time (days)	0.05	24	Replace

5.4.4. Validation

The final step is the validation process. Arnold *et al*. (2012b) describe the process of validation as '…demonstrating that a given site-specific model is capable of making sufficiently accurate simulations'. They highlight that this is however dependant on the specific goals for individual projects (Arnold *et al*, 2012b).

The validation period was from years 2004 to 2010. For validation, the calibrated parameter range is used in one iteration of the same number of simulations as used in the calibration process, which was 500.

CHAPTER 6: RESULTS AND DISCUSSION

6.1. INITIAL RESULTS

The SWAT model was set up and run as described in Chapter 4 on a monthly time basis. The initial run was conducted for 18 years, from 1990 to 2010 with a three year warm up run (NYSKIP) from 1990 to the beginning of 1993. The initial simulated stream flow results were compared with measured stream flow from the DWS flow gauge B7H004 (Figure 6.1). The stream flow gauge B7H004 is located in sub-basin 4 in the B73A watershed (Figure 3.9). The comparison was done for each year, excluding 1999-2003 due to missing flow measurements for these years at gauge B7H004.

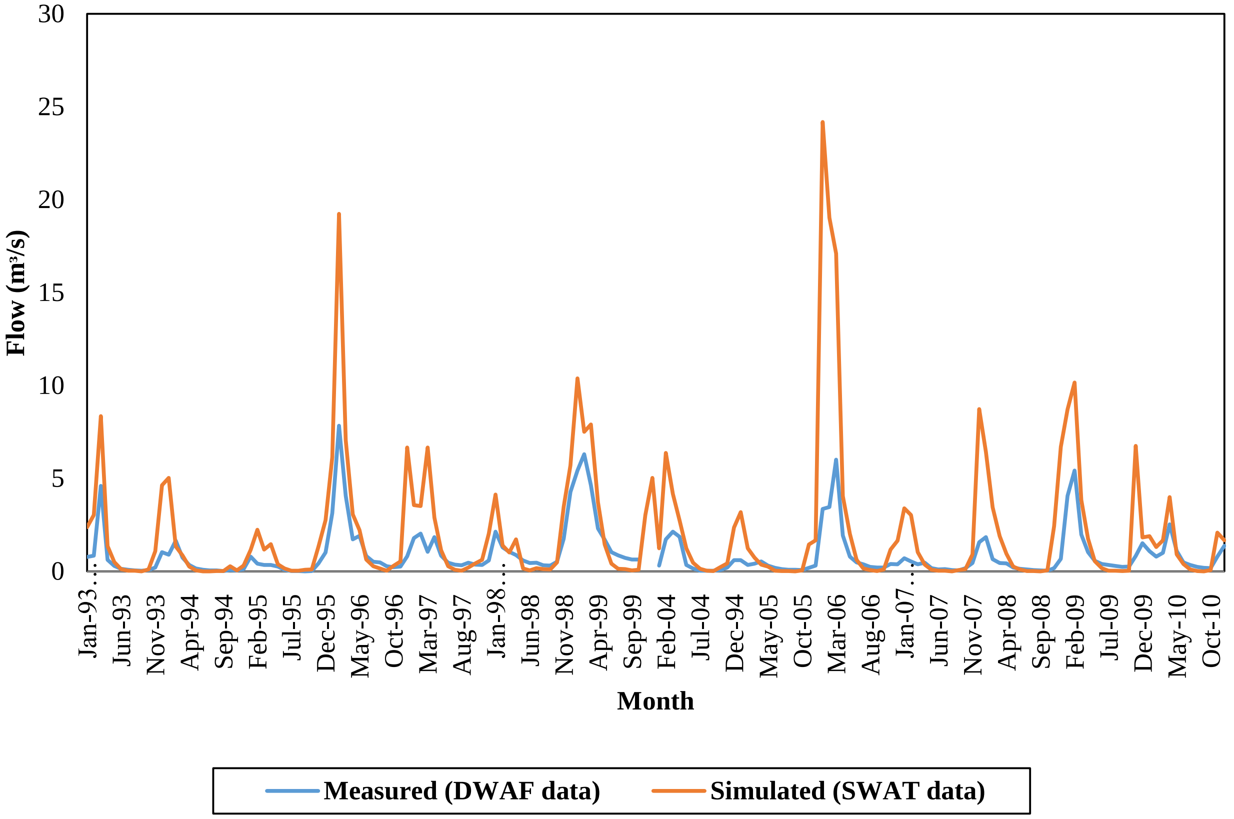


Figure 6.1. Initial comparison between measured and simulated monthly stream flow from stream flow gauge B7H004, located in sub-basin 4 in the B73A sub watershed.

The initial results indicate that the SWAT model in general produces simulated flow that over estimates the peak measured flow and under estimates the measured flow at all other times (Figure 6.1).

Only the NSE was used to judge initial model performance. NSE was calculated using equation (1), and a value of NSE= -3.9 was obtained. According to performance criteria (Moriasi *et al*, 2007), values ≤ 0.0 indicate that the mean observed value is a better predictor than the simulated value and therefore this is unacceptable model performance.

6.2. MANUAL CALIBRATION RESULTS

The runoff curve number (CN2) and the base flow recession constant (ALPHA_BF) were adjusted manually in an attempt to get better NSE results between the observed and simulated data. Although the NSE value increased (NSE= -0.88) the value is still negative which is indicative of unacceptable model performance.

6.3. GLOBAL SENSITIVITY ANALYSIS RESULTS USING SUFI-2

The results of a sensitivity analysis can be used to eliminate non-sensitive parameters from the calibration process (Arnold *et al*, 2012b). The results of the global sensitivity analysis performed in SUFI-2 are shown in Table 6.1. The t-statistic gives a measure of the sensitivity of the parameter, where larger in absolute values are more sensitive. The p-values show the significance of the sensitivity, where p-values closer to zero are more significant.

The most sensitive parameter is the CN2 or runoff curve number, and that sensitivity is highly significant (p-value = 0). Following that, GWQMN and ESCO, the threshold depth of water in the shallow aquifer required for return flow to occur (mm H_20) and the soil evaporation compensation coefficient, respectively, are the next sensitive parameters. The sensitivity analysis highlights the sensitivity of the runoff curve number to such an extent that to calibrate only this parameter would substantially improve results. Therefore for the course of the calibration process, emphasis was placed on this parameter. However, because the majority of the other parameters were also significantly sensitive (close to or equal to zero) all the parameters were used during calibration in SUFI-2. The only potential issue of using a greater number of parameters during calibration would be the time that the program takes to run each iteration. For this study, nine parameters were chosen, and it was decided that although the run time of the program could be shortened if less parameters were chosen, it would not be by much.

Table 6.1. Results of the global sensitivity analysis after the first initial iteration using SUFI-2.

Parameter Name	t-Stat	P-Value
CN2.mgt	-27.03	0.00
GWQMN.gw	4.312	0.00
ESCO.hru	-4.129	0.00
SOL_AWC.sol	3.234	0.001
GW_DELAY.gw	2.798	0.005
GW_REVAP.gw	2.747	0.006
REVAPMN.gw	-1.393	0.164
SURLAG.bsn	-0.944	0.345
ALPHA_BF.gw	0.168	0.867

6.4. UNCERTAINTY IN SUFI-2

The results and subsequent discussion is closely tied into the concept of uncertainty in the modelling process which the SUFI-2 program conceptually accounts for, and is what the accuracy of the results are based on. The process of calibration is an attempt to obtain better parameter values for a given area, ‘thereby reducing the prediction uncertainty’ (Arnold *et al*, 2012b). The concept of uncertainty and how it is incorporated into SUFI-2 will be discussed. Following that, the application of that uncertainty to the calibration of our modelled study area will be examined in the results and discussion.

6.4.1. Uncertainty in the modelling process

There is inherent uncertainty in many aspects of the modelling process (Abbaspour, user group; Moriasi *et al*, 2007; Arnold *et al*, 2012b). This uncertainty can be in the model itself, due to the approximate nature of mathematical equations used to simulate processes (Moriasi *et al*, 2007). It can be due to the lack of knowledge about some physical processes and operational procedures during the modelling process (Moriasi *et al*, 2007). Uncertainty can be because of the amount and quality of all input data, as well as the amount and quality of the measured data used to calibrate the model (Abbaspour, user group; Moriasi *et al*, 2007).

Moriasi *et al*. (2007) state the following '…although proper model calibration is important in reducing error in model output, experience has shown that model simulation results may contain substantial errors.' Haan *et al*. (1998) furthermore state that '…rather than providing a point estimate of a given quantity of model output, it may be preferable to provide an interval estimate with an associated probability that the value of the quantity will be contained by the interval.' This is in essence an analysis of the uncertainty which is contained in a model.

6.4.2. How uncertainty is accounted for in SUFI-2

In the SUFI-2 program parameter uncertainty accounts for all sources of uncertainty such as uncertainty in input variables (climatic variables), in the conceptual model, parameters and measured data. The degree to which all uncertainties are accounted for is quantified by a measure called the P-factor, which is the percentage of measured data bracketed by the 95PPU or 95% prediction uncertainty (Abbaspour, 2014). This is then a measure of the strength of the uncertainty analysis and calibration.

The R-factor is another measure to quantify the strength of the uncertainty analysis and calibration. The R-factor is the average thickness of the 95PPU band divided by the standard deviation of the measured data (Abbaspour, 2014). SUFI-2 aims to bracket most of the measured data with the smallest 95PPU band or uncertainty band. It starts by assuming a large parameter uncertainty range, although it must be physically meaningful, ensuring that all measured data initially falls within the 95PPU. The uncertainty is then decreased in steps while monitoring the P-factor and the R-factor. The ranges of the parameter values are thus updated in such a way that the new range is always smaller than the previous range (in the previous iteration) (Abbaspour, 2014).

When a simulation corresponds exactly to measured data, the resulting P-factor will be a value of 1 and the R-factor will be zero. Therefore larger values of the P-factor and smaller R-factor values indicate a simulation that contains less uncertainty.

6.5. CALIBRATION RESULTS

The parameter ranges that were used in the final iteration in SUFI-2 which gave adequate values for both the P-factor and R-factor are shown in Table 6.2. Iterations following this were less optimal when considering the two criteria (P-factor and R-factor). This parameter range was subsequently used for validation.

Table 6.2. Parameter value range for the last iteration run during calibration with SUFI-2 that produced acceptable values of the P-factor and R-factor.

Parameter Name	Calibrated Parameter Range	
	Min	Max
GWQMN.gw	0	370.243
ALPHA_BF.gw	0.269	0.756
GW_DELAY.gw	85.370	169.265
GW_REVAP.gw	0.09	0.163
SURLAG.bsn	6.477	11.627
CN2.mgt	43.485	65.256
REVAPMN.gw	54.346	193.683
SOL_AWC.sol	0	0.419
ESCO.hru	0	0.358

The results from the last iteration run in SUFI-2, which produced acceptable results are displayed graphically in Figure 6.2. R-factor of 0.67 (out of a perfect 0). An R- factor below one is considered to signify a narrow 95PPU band (Schuol *et al*, 2008a). 68% of the measured monthly runoff values could be captured by the 95PPU band (out of a perfect 100%). In this figure, the lower and upper 95PPU is shown- the area between the two 95PPU lines is the 95PPU band and illustrates the R-factor (0.67). The degree to which the measured/observed data line falls in between the lower 95PPU line and the upper 95PPU line illustrates the P-factor (0.68) (Figure 6.2).

For evaluation of model performance in terms of quantitative statistics that measure the agreement between simulated and observed flow values NSE, PBIAS and R^2 were used as criteria. The objective function was specified as NSE > 0.5, and this was achieved during calibration, where the NSE was 0.8 (Table 6.3). The performance rating is considered to be very good for 0.75< NSE ≤1.00 (Saleh *et al*, 2000; Moriasi *et al*, 2007). The NSE, as well as other statistical measures comparing the observed data to calibrated simulated data in SUFI-2 are shown in Table 6.3. This includes the percent bias (PBIAS) and the correlation (R^2). The results from the SUFI-2 calibration process indicated a good performance with a PBIAS value of 12.6% (Table 6.3). The R^2 value was 0.83 indicating a good correlation between observed and simulated values (Table 6.3).

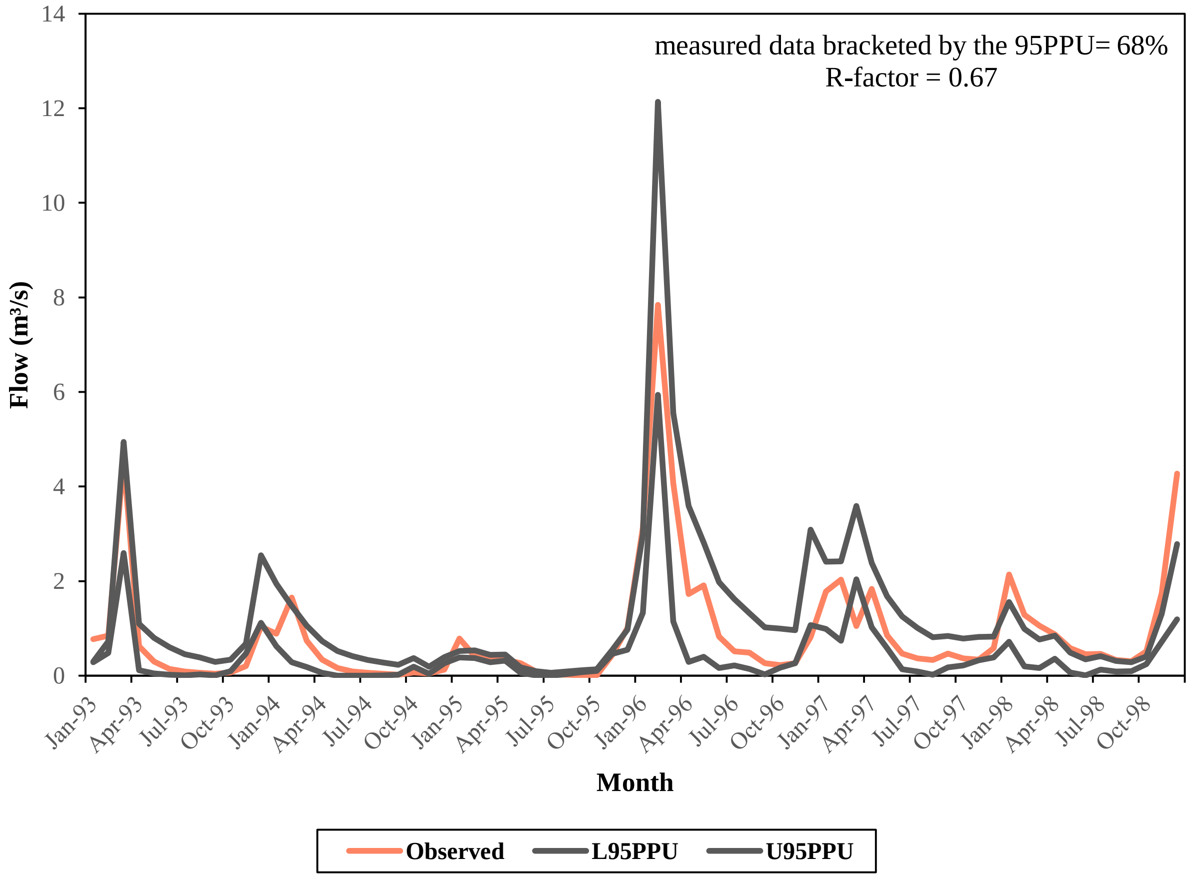


Figure 6.2. Calibration results from SUFI-2 comparing the measured flow (m3/s) from gauge B7H007, years 1993-1998, to the 95PPU lower (L95PPU) and upper (U95PPU) limits. The 95PPU limits illustrate the parameter ranges that most closely resemble observed flow during the calibration process.

6.6. VALIDATION RESULTS

The results for validation using the calibrated parameter range are displayed in Figure 6.3. For the validation period, 71% of the observed or measured data fell into a slightly larger 95PPU band than the calibration period (R-factor of 1.12 as compared to R-factor of 0.67 for calibration). The R-factor is acceptable at 1.12, as it is still approximately 1.0 (Schuol *et al*, 2008a).

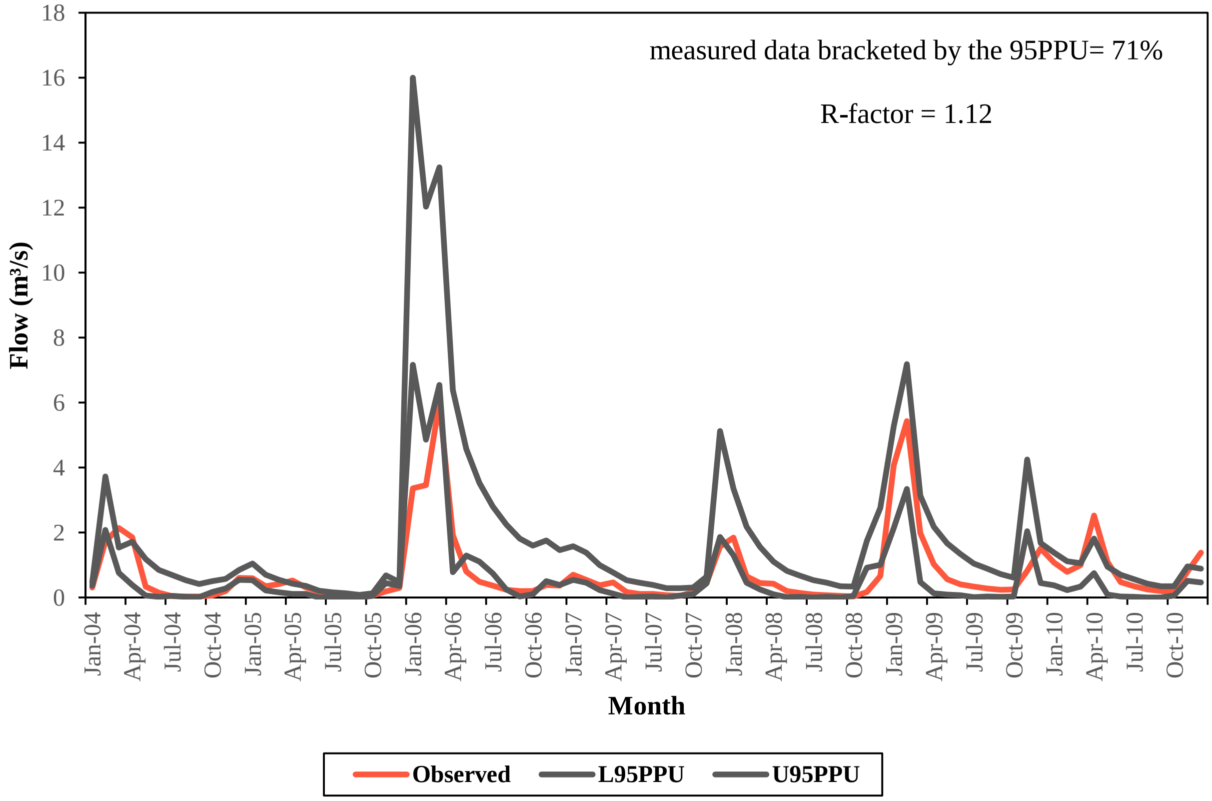


Figure 6.3. Validation results in SUFI-2 comparing observed flow from gauge B7H007 for year 2004-2010, and the 95PPU lower (L95PPU) and upper (U95PPU) limits. The 95PPU limits illustrate the parameter ranges that most closely resemble observed flow during calibration.

The NSE value for validation was 0.46 (Table 6.3). Although this does not meet the objective function of >0.5 specified in SUFI-2, Moriasi *et al*. (2007) state that values between 0.0 and 1.0 are generally viewed as acceptable levels of performance. Values of NSE that are < 0 indicate that the mean observed value is a better predictor than the simulated value, indicating unacceptable performance. The PBIAS for validation was 26.1% which is unsatisfactory. R^2 = 0.62% which is acceptable.

Table 6.3. Results of the quantitative statistical analysis that were chosen to evaluate model performance i.e. compare observed and simulated monthly surface water flow during the calibration (1993-1998) and validation (2004-2010) period.

	Nash-Sutcliffe Coefficient	**PBIAS**	**Correlation (R^2)**
Calibration	0.80	12.6	0.83
Validation	0.46	26.1	0.62

6.7. DISCUSSION

The initial comparison between measured and simulated monthly flow was statistically unacceptable. The model substantially over simulated the peak flows. The noticeably high sensitivity of the CN2 or runoff curve number is consistent with other studies conducted using the SWAT model (Govender and Everson, 2005; Qi and Grunwald, 2005; Schuol *et al*, 2008a; Getachew and Melesse, 2012; Noor *et al*, 2014). Qi and Grunwald (2005) state '…the land use determined the CN2 numbers, which describe the process of infiltration and surface runoff'. CN2 values that had not been correctly calibrated could be a reason for the high peak flows during model simulation. It should be noted that this cannot be the only reason, as the manual calibration- which only calibrated the CN2 and ALPHA_BF values, although improved results substantially, still did not produce acceptable model simulations. The simulation of runoff is a result of many different processes and parameters in the SWAT model.

The results are particularly good for the calibration period of the model. This includes the graphical comparison which takes into account all forms of uncertainty which the SUFI-2 program is able to do (P- and R- factor), as well as the quantitative statistical analysis. When the calibrated model was validated results were poorer, particularly for the quantitative analysis. The model was still able to bracket a large portion of the observed data within a small uncertainty band, as displayed graphically. The NSE was also still acceptable.

The results show that the model was able to simulate peak and low flows adequately, as shown by the R^2 statistical measure ($R^2>0.5$), for both calibration and validation. The statistic that was considered unacceptable during validation was the PBIAS. The high positive value for PBIAS indicates that the model had a bias towards underestimating the flow (Moriasi *et al*, 2007). Abbaspour (2014) explains that the choice of objective function in SUFI-2 can affect the solution given by the program, which could be a potential reason for this result. It would be best, when examining the results, to focus on the statistic that is set as the objective function (in this case the NSE). It could also be due to conditions during the validation period varying substantially from the calibration period, although this is doubtful as the other measures of evaluation for the validation could still be considered acceptable. In general, Moriasi *et al* (2007) state that stricter performance ratings should be required during model calibration as compared to validation.

The use of NSE for the objective function should be discussed. Although widely used and accepted in literature (ASCE, 1993; Moriasi *et al*, 2007; Fadil *et al*, 2011; Mango *et al*, 2011), there are also some negative issues that should be considered. Legates and McCabe (1999) highlight the fact that because the differences between the observed and simulated values are squared, larger values in a time series will be strongly overestimated and lower values will be neglected. This means that for flow calibration and validation- the efficiency measure NSE is focused on the peaks and high flows and therefore less focused on the low flow predictions (Krause *et al*, 2005; Qi and Grunwald, 2005). However, this measure was decided to be adequate for this study. Considering our initial results (figure 6.1) before calibration, the trend seems to be a much higher simulated peak flow value - more so than the under-prediction of the troughs. The focus that NSE places on the peak values may well be helpful during the calibration and validation process. It could also be a potential explanation as to why the PBIAS value during the validation period indicates that the model is bias towards underestimation. The focus that NSE places on correcting peak flows, could mean that this was what was essentially “corrected for” during model calibration.

In this study, there was only one available stream flow gauge in the catchment area. Qi and Grunwald (2005) state ‘…the more calibration and validation stations are available to adjust a model such as SWAT to local and regional watershed characteristics, the better will be the prospects for reliable simulations of water flow.’ This would also result in increased confidence when using the model to predict different scenarios and to predict flow in ungauged stations. Similarly, the input climate data, other than rainfall data, was downloaded from a global weather data website, of which data quality for such a small, localised area could be questionable. Luckily rainfall data was available for our catchment area from a weather station located inside the catchment, and this data was used together with the global weather data station data for rainfall input. There is also potential for uncertainty in the modelling process introduced by the method of obtaining measured stream flow (Harmel *et al*, 2006).

Another limitation of the use of the SWAT model in a mountainous catchment in Africa would be the limited availability of soil data, as well as base flow data. The soil parameters used for input into the model for our catchment area were estimates, and this could introduce substantial amounts of uncertainty in the modelling process. Similarly, the SWAT database for land use parameters was used, and these are based on American vegetation cover types. Although this is suggested to be adequate (Dabrowski, 2013), it could still have caused some uncertainty whilst modelling our catchment. For the calibration of the model, runoff was focused on. This was due to the fact that no base flow data was available. Similarly no river abstraction data was available. However, most of the catchment area lies in a protected area- either due to the protection of natural area or due to forestry. This means there is in general limited access to the area of the catchment lying in the mountains which will limit the amount of abstraction taking place.

The SWAT model is an extremely comprehensive model with a high number of parameters. This has been described as a weakness of the model, in the sense that a high number of parameters will complicate the model parameterization and calibration process (Arnold *et al*, 2012b). For a mountainous region being modelled, this could be an exacerbated issue due to the fact that one of the most well-known characteristics of these areas is their complexity (Chaponniere *et al*, 2008).

The overall results of this study demonstrate that the SWAT model, once parameters are within a sufficient calibrated range, can provide reasonable simulations of monthly run-off in the B73A catchment. This is a similar finding to other research conducted in Africa, which also found that the SWAT model could produce reasonably comparable observed and simulated flow data (Govender and Everson, 2005; Birhanu *et al*, 2007; Mango *et al*, 2011; Mutenyo *et al*, 2011; Noor *et al*, 2014; Ridwansyah *et al*, 2014). In particular, a study by Birhanu *et al* (2007) examined the applicability of the SWAT model in a mountainous catchment in Northern Tanzania and obtained good results stating that '…the SWAT model can be a potential monitoring tool for watersheds in mountainous catchments'. Mutenyo *et al*. (2011) applied the SWAT model in a mountainous region in Eastern Uganda and found that the model was able to simulate monthly flow data successfully in their catchment. The hydrology of the Cisadane area, a mountainous catchment in Indonesia was successfully modelled by using SWAT (Ridwansyah *et al*, 2014). Noor *et al*. (2014) found that the SWAT model was able to accurately predict hydrology of the semi-arid Taleghan mountainous watershed.

The ability of the SWAT model to simulate runoff to an adequate evaluation criteria was only achieved after a careful and relatively time-consuming effort of calibrating certain SWAT model parameters, in an attempt to better represent the study catchment area. The importance of parameterization is also highlighted in similar research conducted in South Africa by Govender and Everson (2005) using the SWAT model in two small experimental catchments. They state that when the SWAT model is applied to South African catchments, it is important to parameterize the model as accurately and efficiently as possible for the local conditions (Govender and Everson, 2005). In a more global study conducted by Winiger *et al*. (2005) in the Himalayas, the importance of globally remote sensing techniques and runoff models as a way to better understand mountain hydrology was highlighted, although they state that the models need to be improved and adapted to the region of interest.

In order to parameterize and adapt the SWAT model more thoroughly to the area of interest however, the user would in essence need access to more data, or data of a higher quality. Scarce data is identified as a prominent issue in hydrological modelling, particularly in Africa and in mountainous areas (Alford, 1985; Klemes, 1990; Messerli *et al*, 2004; Jayakrishnan *et al*, 2005; Chaponniere *et al*, 2008; Schuol *et al*, 2008a; Schuol *et al*, 2008b; Mango *et al*, 2011; Mutenyo *et al*, 2013). Mutenyo *et al*. (2013) found that for their particular mountainous catchment area, to achieve results that would enable them to adequately simulate daily stream flow, they would need more weather stations to 'capture microclimates' within their study area. Jayakrishnan *et al*. (2005) applied the SWAT model in the Bosque river basin in Texas, as well as in the Sondu river basin in Kenya, and state that the model has good potential to be applied worldwide and can be used to save time and money during watershed management and decision making. However, they also point to the fact that in Africa there is a need for datasets to be developed for input variables (Jayakrishnan *et al*, 2005). Schuol *et al*. (2008b) applied the SWAT model to the whole of Africa. They found that although their results were generally good, there were large prediction uncertainties in some cases due to a lack of input databases (Schuol *et al*, 2008b).

The use of a semi-automated program such as SUFI-2 in SWAT-CUP, which incorporates all forms of uncertainty in the modelling process, as well as manual calibration coupled with a sound knowledge of the catchment area's hydrology, would possibly enable adequate modelling. Ridwansyah *et al*. (2014) used SUFI-2 procedures and found it was successful in minimizing the differences between observed and simulated data. Schuol *et al*. (2008b) used the SUFI-2 program to successfully calibrate and validate SWAT modelled areas across the whole of Africa. The prediction uncertainties were also quantified using the program (Schuol *et al*, 2008b).

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

This study aimed to focus on the hydrological modelling of a mountainous region in South Africa. The Mariepskop mountain is one of the highest mountains in the Mpumalanga Province of South Africa. The B73A quaternary catchment, which contains the Mariepskop mountain, is therefore mountainous in nature. The catchment area had a stream gauge location with readily available data, as well as rainfall data from a weather station located just outside the catchment area. The top most parts of the mountain are reserved areas. Large parts of the rest of the mountain are used for forestry. This means the runoff originating from this mountain is of relatively good quality. As the mountain supplies surrounding lowland townships with water, it is an important water tower. The reserved area, as well as the whole catchment area, is also an important area for biological diversity. The catchment area is therefore an important area to study and manage. This made it an ideal watershed in which to examine the ability of a hydrological model to model runoff from a mountainous area.

The SWAT model was then applied to the B73A catchment. The model was successfully run using the GIS interface which provided a user friendly method of inputting data into the SWAT program. The SWAT model was able to successfully simulate stream flow data from the catchment area.

The SWAT model was able to simulate surprisingly reasonable monthly runoff values, when it was calibrated and validated using the SUFI-2 program in SWAT-CUP. The catchment area is expected to be complex due to its mountainous nature, and data was relatively limited in the study. Specifically most of the climate input data was of a questionable quality, as well as the soil data. The results of simulation during calibration were very good. However, during the process of validating the model, results achieved were generally poorer than calibration, although termed ‘adequate’ by evaluation criteria standards (Moriasi *et al*, 2007). This is similar to results of other studies in literature (Mango *et al*, 2011).

It is believed that the results from this study show that that the SWAT model was able to simulate flow adequately and the model could potentially be used in other ungauged catchment areas with similar land use and climate. The model has potential to be used for future scenario analysis, as well as in water resource planning and management although an amount of caution would need to be exercised. It would be extremely useful to calibrate the base flow data that the model produces, as well include climate data that originates in the catchment area. This would make the results of the model substantially more accurate.

This project can be regarded as an exploratory analysis of the suitability of the SWAT hydrological model to simulate monthly runoff values in a mountainous catchment area. This study has therefore demonstrated the ability of a semi-distributed hydrological model – the SWAT to adequately simulate the runoff from a small mountainous catchment area in South Africa.

7.2. RECOMMENDATIONS

The recommendations are as follows, and are a few views and perspectives on the project as a whole:

- The use of the SWAT model was greatly aided by the vast amount of user-support provided. This includes: the GIS interface tools, the user-support groups both for the SWAT model and for the SWAT-CUP program, SWAT literature database, web-based documentation and educational videos on the SWAT website.

- In order to improve the ability of runoff modelling to accurately simulate flow, an increase of available data would be needed. More data, especially observed flow and rainfall data, would allow for the accounting of spatial variability within the catchment areas modelled and more accurate parameterization and calibration.

- Calibrated models of catchment areas can be used to assess the potential impacts of continued land use change; possible increases in abstraction and climate change on the runoff. This can be an extremely important tool used in water resource management and planning. This is particularly true for African watersheds, where water security is an issue.

- Calibrated models can also be used to assess water resources in adjacent ungauged watersheds- if conditions such as land use and soil variables are similar.

- The SWAT model was not used to its full ability in this study, due to the scope of the project, as well as limited datasets. The SWAT model is able to simulate sediment loading as well as different land use management practises during agriculture. Therefore there is a lot of potential to use this model in the B73A catchment for other purposes, if the relevant data is obtained.

- This project contains a very detailed account of how the SWAT model was set up and run in this particular catchment. It can be a useful guide for other research that may focus on hydrological modelling.

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