EVALUATION OF THE SWAT MODEL IN SIMULATING CATCHMENT HYDROLOGY: CASE STUDY OF THE MODDER RIVER BASIN

by

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A dissertation submitted in fulfilment of the requirements for the degree

Magister Technologiae (Engineering: Civil)

in the

Department of Civil Engineering

of the

Faculty of Engineering and Information Technology,

of the

Central University of Technology, Free State, South Africa.

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November 2013

DECLARATION

I, the undersigned, declare that the dissertation hereby submitted by me for the degree *Magister Technologiae* (Engineering: Civil) at the Central University of Technology, Free State, is my own independent work and has not been submitted by me to another University and/or Faculty in order to obtain a degree. I further cede copyright of this dissertation in favour of the Central University of Technology, Free State.

Samuel Tshehla TETSOANE

Signature: ………………………….

Date: ....

Bloemfontein, South Africa

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Prof. Y.E. Woyessa, for his contribution, guidance, patience and encouragement throughout this research project.

Also, my great appreciation to my co-supervisor, Dr W.A Welderufael, for his unreserved sharing of his expertise, contribution and advice on this project.

A special word of thanks to my wife and daughter, my parents as well as my brother for their love and being part of my life.

ABSTRACT

Hydrological models have become vital tools for understanding hydrologic processes at the catchment level. In order to use model outputs for tasks ranging from regulation to research, models should be scientifically sound, robust, and tenable. Model evaluation is therefore beneficial in the acceptance of models to support scientific research and to guide policy, regulatory, and management decision-making. The objective of this study was to evaluate the performance of the SWAT model in simulating stream flow for the Modder River Basin. The study area is situated at -29° 11' latitude and 26° 6' longitude at an elevation of 1335 m and drains a land area of 949 km^2. The land cover is mainly grassland (pasture) with other minor land use types. The climate of the area is semi-arid with Mean Annual Precipitation (MAP) of 563 mm. Two techniques that are widely used in evaluating models, namely quantitative statistics and graphical techniques, were applied to evaluate the performance of the SWAT model. Three quantitative statistics, namely Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the mean square error to the standard deviation of measured data (RSR), in addition to the graphical techniques, were identified to be used in model evaluation. Results of calibration and validation of the model at a monthly time step gave NSE of 0.65, Pbias of 15 and RSR of 0.4, while NSE of 0.5, Pbias of 31 and RSR of 0.5 were recorded for validation. According to monthly model performance ratings, the model performed well during calibration and performed satisfactory during the validation stage.

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LIST OF ABBREVIATIONS

ACRU	Agrohydrological modelling system
Agri-Con	Maize planted with conventional tillage
Agri-IRWH	Maize planted with Infield Rainwater Harvesting
AGRR	Agricultural Land
AnnAGNPS	Annualised Agricultural Nonpoint Source Pollution Model
ANSWERS-2000	Areal Nonpoint Source Watershed Environment Response Simulation – 2000
CN	Curve Number
DEM	Digital Elevation Model
DWA	Department of Water Affairs
GCS	Geographic Geodetic System
GIS	Geographic Information System
HRUs	Hydrologic Response Units
HSPF	Hydrological Simulation Program in FORTRAN
MAE	Mean Annual Evaporation
MAP	Mean Annual Evaporation
MAR	Mean Annual Runoff
NSE	Nash-Sutcliffe Efficiency
PBias	Percent Bias
RMSE	Root mean square error

RSR	Ratio of root mean square error and standard deviation
SAWS	South African Weather Services
SWAT	Soil and Water Assessment Tools
SWMM	Storm Water Management Model
URBN	Urban land
WETN	Wet land
WGS	World Geodetic System

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CHAPTER 1: INTRODUCTION

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1.1 Introduction

According to Synder and Stall (1965, cited in Minnesota Pollution Control Agency, 2000), a model is defined as “the symbolic form in which a physical principle is expressed. It is an equation or formula, but with the extremely important distinction that it was built by consideration of the pertinent physical principles, operated on by logic, and modified by experimental judgment and plain intuition.”

Hydrological models have become vital tools for understanding hydrologic processes at the catchment level and are used extensively for hydrologic predictions. Hydrological models assist in answering questions with regard to the effect of land management practices on quantity and quality of runoff, infiltration, subsurface flow (both unsaturated and saturated) and deep percolation. The objective of hydrologic system analysis is to understand the system operation and predict its output (Chow et al., 1988). These hydrological models rely on observed (measured) data to simulate or predict the hydrologic response of the catchment and, unlike in poorly or un-gauged catchments, they can be tested in well-gauged catchments (Ndomba et al., 2008).

Beven (2001) breaks down the development of a hydrological model into the following steps:

a) The perceptual model: deciding on the processes

The perceptual model is the summary of our perceptions of how the catchment responds to rainfall under different conditions, or rather, our perceptions of that response.

b) The conceptual model: deciding on the equations

Mathematical description is, traditionally, the first stage in the formulation of a model that will make quantitative predictions. At this point the hypotheses and assumptions being made to simplify the description of the process need to be made explicit.

c) The procedural model: developing the model code

If the equations cannot be solved analytically, given some boundary conditions, for the real system (which is usually the case for the partial differential equations found in some hydrological models), then an additional stage of approximation is necessary using the techniques of numerical analysis to define a procedural model in the form of code that will run on a computer.

Soil and Water Assessment Tool, commonly known as SWAT, is a semi-distributed basin scale hydrological model in which the catchment is divided into multiple sub-catchments which are further subdivided into hydrologic response units (HRUs) that consist of homogenous land use, management and soil characteristics. The HRUs represent percentages of the sub-catchment area and are not identified spatially within the SWAT simulation.

Spatial (Digital Elevation Model, Soil, and Land Use) data are pre-processed in Geographical Information Systems (GIS) and input into SWAT via the interface. Daily precipitation and minimum and maximum temperature are primary input climate data. Other climate data such as solar radiation and wind speed can be simulated by the SWAT weather generator. The SWAT model will simulate movement of water through the catchment/watershed. Sensitivity analysis and auto-calibration tools are incorporated into the SWAT model.

Models are evaluated using statistical indices. Statistical evaluation of a model is extensively discussed by Willmott et al. (1985), Loague and Green (1991), Krause et al. (2005), Moriasi et al. (2007) and other efficiency criteria measures are reported as well.

1.2 Problem statement

The whole Modder River Basin is a large basin with a total area of 17 366 km^2. It is divided into three sub-basins, named as the Upper Modder, the Middle Modder and the Lower Modder. C52 is located within the Upper Orange Water Management Area to the east of the City of Bloemfontein (located in the Free State Province in central South Africa). The mean annual rainfall of C52 catchment is 537 mm and with mean annual runoff (MAR) of 94.4×10^6 m^3 (Woyessa et al., 2006). The climate of the area is semi-arid. According to Rockström (2000), the mean annual rainfall of semi-arid zones varies from 400 mm to 600 mm and ranges between 200 mm to 1000 mm for dry semi-arid to dry sub-humid zones.

The Modder River plays an important role in supplying water to several users, namely domestic, agricultural as well as industrial. As such these water users are heavily dependent on the Modder River. According to some estimates, the Modder River is already exploited to the limits of sustainability (River Health Programme, 2003) and this has necessitated transfers of water from the Caledon River to meet the needs of the user groups through the Novo Transfer Scheme (Slabbert, 2007). BKS (2003) reported that the water balance of the Modder/Riet catchment indicates the deficit which is otherwise balanced through the above-mentioned Novo Transfer Scheme. This exploitation accentuates the need for effective and sustainable water resource management through better understanding of the hydrologic processes in the catchment.

Thus, in order to understand the hydrological process of a catchment and evaluate a selected hydrological model in simulating a catchment's stream flow, quaternary catchment C52B within C52 tertiary catchment was identified. The hydrologic process of the C52B quaternary catchment was simulated using the Soil and Water Assessment Tool (SWAT) model. The model (SWAT) set-up was followed by model evaluation in simulating stream flow and also with a view on its possible use for similar purposes in other catchments in the future.

1.3 Hypothesis

The Soil and Water Assessment Tool (SWAT) model can be effectively used to simulate hydrologic response (stream flow) at catchment level.

1.4 Aim of the study

The aim of the study was to investigate into a hydrological model that is capable of simulating the water yield of un-gauged catchments and other data scare catchments.

1.5 Objectives

The objectives of the study were:

a) To set up the SWAT model for the catchment condition and run the model.

b) To calibrate and validate the SWAT simulation results.

c) To assess the performance of the SWAT model using efficiency criteria.

CHAPTER 2: LITERATURE REVIEW

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2.1 Catchment hydrology

Catchment hydrology deals with surface and ground waters on a landscape scale where the unit of interest is the catchment. The catchment refers to the land area that is drained by one river and its tributaries.

2.1.1 Hydrology

According to Chow et al. (1988), hydrology may be defined more strictly as the study of the hydrologic cycle, i.e. the endless circulation of water between the earth and its atmosphere. The hydrologic cycle, also called the water cycle, refers to the pathway of water in nature as it moves in its different phases through the atmosphere, down over and through the land, to the ocean and back up to the atmosphere (Brutsaert, 2005). Chow et al. (1988) describe the hydrologic cycle as follows:

> "the cycle has no starting or ending point. Water evaporates from the oceans and lifted in the atmosphere until it condenses and precipitates on the land or the oceans; precipitated water may be intercepted by vegetation, become overland flow over the ground surface, infiltrate into ground, flow through the soil as subsurface flow, and discharge into streams as surface runoff. Much of the intercepted water and surface runoff returns to the atmosphere through evaporation. The infiltrated water may percolate deeper to recharge groundwater, later emerging in springs or seeping into streams to form surface runoff, and finally flowing out to the sea or evaporating into the atmosphere as the hydrologic cycle continues."

Fig. 2.1 illustrates the hydrological cycle and its major components.

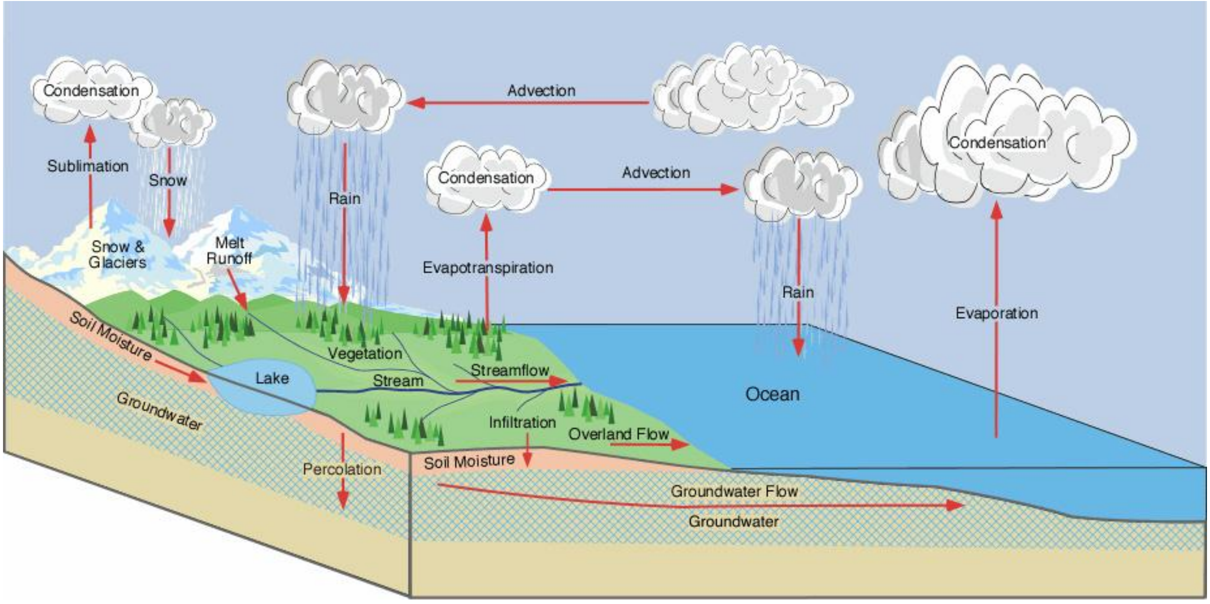

Fig. 2.1: Hydrologic cycle (Pidwirny, M., 2006).

2.1.2 Catchment

Catchment (also sometimes referred to as drainage basin or river basin) is defined as an area drained by a stream or stream channel networks such that all the surface runoff originating in this area leaves the area in a concentrated flow through a single outlet (Reddy, 2006). Quantitative assessment of hydrological parameters like precipitation, evaporation, infiltration and runoff, and their use in water balance studies or in the problems of design and forecasting, will be rational only when they are applied to an area with well-defined boundaries (Reddy, 2006).

Runoff is a product of a hydrologic cycle which is influenced by two major factors, namely physiographic factors and climatic factors. Physiographic factors are further classified into two forms: catchment characteristics and channel characteristics. Catchment characteristics include land use and cover, soil type, topography and slope. Channel characteristics are related mostly to hydraulic properties of the channel which govern the movement of stream flows and determine channel storage capacity (Chow, 1964). Climatic factors include type of rainfall, areal distribution of rainfall, duration of rainfall, intensity of rainfall, antecedent rainfall, direction of the storm movement and other factors that affect evaporation and transpiration (Reddy, 2006). A selection of these factors is discussed in further detail below.

2.2 Catchment characteristics

2.2.1 Land use and cover

Land use/cover refers to natural vegetation cover and the human activities that are directly related to land, making use of its resources and interfering in the ecological process that determine the functioning of land cover (Niehoff et al., 2002). It is a well-established fact that land use is one of the key parameters in the hydrologic cycle (Giertz et al., 2005).

The impact of land use change on the hydrologic processes in the tropics was particularly investigated in terms of rainforest conversion during the 1980s and 1990s (Giertz et al., 2005). In a study conducted by Hundecha and Bárdossy (2004) it was found that urbanization leads to a 2.9% increase in the peak flow following a summer storm while an increase in the peak flow for winter rainfall has been found to be relatively low. A decrease of 14% on peak flows due to increased afforestation was also reported by Hundecha and Bárdossy (2004). Tang et al. (2005) reported a 5% - 12% increase on runoff due to urbanization. Klöcking and Haberlandt (2002) also found that urbanization causes an increase of storm flows in relation to the increased amount of surface runoff.

In a study conducted in the central region of South Africa, Welderufael et al. (2013) reported the following water yield results: 89 mm/year, 84 mm/year and 83 mm/year for different land use scenarios, namely maize planted with conventional tillage (Agri-CON), pasture land (PAST) and maize planted with infield rainwater harvesting (Agri-IRWH).

The studies on the impact of grazing pressure on hydrological processes also ascertain that high grazing pressure promotes high surface runoff by reducing vegetation cover, increasing compaction and lowering infiltration rate (Girmay et al., 2009). Kashaigili (2008) concluded that the modification of the land use and cover has resulted in changes in temporal distribution of runoff within the catchment. Wei et al. (2007) reported the following runoff coefficients for different land use types: 8.40% for cropland, 7.16% for pastureland, 2.61% for shrubland, 5.46% for woodland and 3.91% for grassland. Giertz and Diekkrüger (2003) indicated the impact of land use on runoff generation by infiltration measurements on different land use types, cultivated land and natural vegetation land, where cultivated land showed a lower infiltration rate which resulted in higher surface runoff generation than other land use types.

2.2.2 Soil type

According to Schaetzl and Anderson (2005), soil means different things to different people. Engineers, for example, view soil as material that can be used in construction and as a medium for foundations; farmers view soil as a medium where they can grow crops; pedologists, then again, view soil simply as something natural, formed on the earth's surface. Fig. 2.2 below shows components of most/ideal soils.

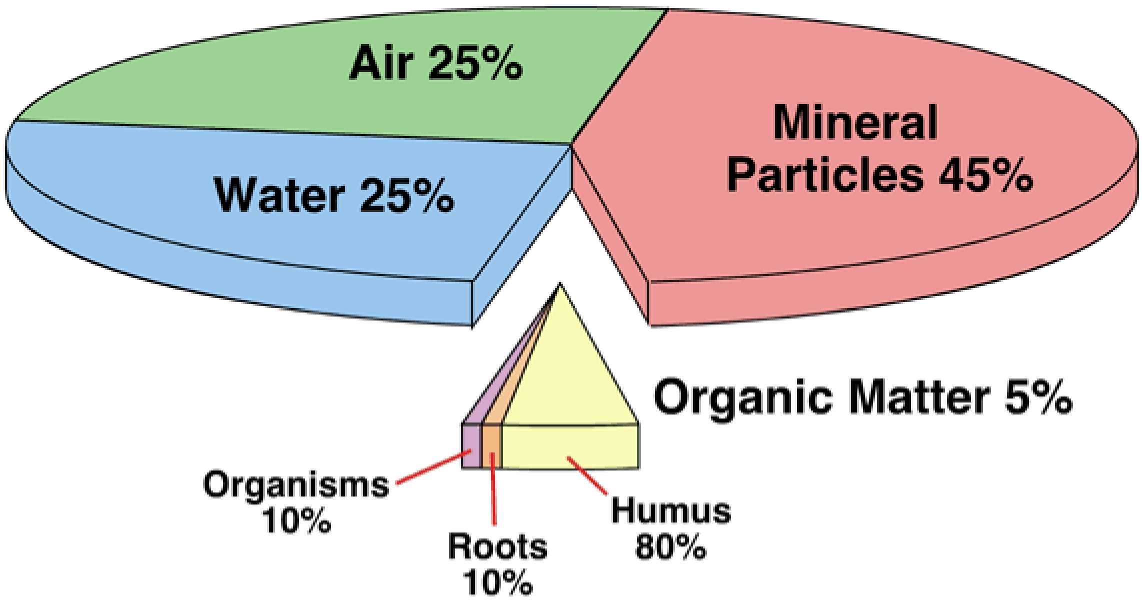

Fig. 2.2: Four basic components of most soils: mineral particles, water, air, and organic matter (Adopted from Pidwirny, 2006.)

The texture of a particular soil refers to the size distribution of the particles found in a representative sample of that soil (Pidwirny, 2006). Soil texture and coarse fragment content are most important properties for a number of reasons, but most importantly they affect the way water moves through and is retained in the soil (Schaetzl & Anderson, 2005). Different soil types affect runoff generation differently. In their study of Trinidadian soils, Ekwue and Harrilal (2010) reported the following mean runoff values: 22.2 mm, 22.9 mm and 40.9 mm for the sandy loam, clay loam and clay soils respectively.

2.2.3 Topography

Topography represents the contour or arrangement of land surface including its relief and the position of its natural and man-made features (Krause, 2008). Topographic maps are usually used to show areas of different elevations on the area. For example, elevations of mountains and valleys, steepness of slopes, and the direction of stream flow can be determined by studying topographic maps (Gabler et al., 2004). Hydrologists use topographic and soil maps as starting point when studying an area (Bouma, 1986; cited by Ward & Robinson, 1990). Besides surface water, topography of the land surface also determines the general direction of groundwater flow, and it influences groundwater recharge and discharge (Krause, 2008).

2.2.4 Slope

Larger slopes generate more velocity than smaller slopes and hence can dispose of runoff faster. Hence, for smaller slopes, the balance between rainfall input and the runoff rate gets stored temporally over the area and is able to drain out gradually over time. Haggard et al. (2005) as well as Khan et al. (2007) reported that an increase in surface slope showed an increase in surface runoff.

2.3 Climatic factors

a) Rainfall types

Rainfall is the most important data required in any rainfall-runoff models. The availability of precipitation data and its duration are vital for hydrologic analysis and design of water resources systems (Teegavarapu & Chandramouli, 2005). Suhaila and Jemain (2009) described three types of rainfall: convectional rainfall, frontal or cyclonic rainfall, and orographic rainfall. Convectional rainfall, associated with hot air, mostly occurs in the tropics. It is brought about by rising and abrupt cooling of air that has been warmed by the extreme heat of the ground surface. If the air is hot enough, it rises very quickly and can cause thunderstorms.

Frontal rainfall occurs when warm air is forced to rise over cold air. The moisture in the warm air condenses as it cools, which creates clouds which in its turn leads to rain. On the other hand, orographic rainfall occurs when airstream is forced to rise over a mountain range where air becomes cooled and rain takes place. Because of the orographic effect, the windward slope of large topographical configurations typically receives more rain than the leeward slope (Blocken et al., 2005). The influence of topography on rainfall distribution can be attributed to one of two different mechanisms, both wind-driven: the orographic effect, or the small-scale topographic effect (Sharon & Arazi, 1997; Blocken et al., 2005).

b) Areal distribution of rainfall

Quantitative estimation of the spatial distribution of rainfall is required for various purposes including water resources management, hydrologic modelling, flood forecasting, climate change studies, water balance computations, soil moisture modelling for crop production and irrigation scheduling (Basistha et al., 2008). Rainfall data is captured by rain gauges spread over the catchments at different distances from each other. The estimation of the average rainfall over a catchment area (river basin), from data taken at several measurement stations, is an important stage in many hydrological applications (Pardo-Igúzquiza, 1998 citing Bras & Rodriquez-Iturbe, 1976; Chua & Bras, 1982; Bastin et al., 1984). Dirks et al. (1998) reported that problems facing meteorologist and hydrologists studying spatial rainfall patterns are the interpolation of data from irregularly spaced rain gauges in order to determine mean areal rainfalls or to characterize rainfall variability within a region or catchment. Different interpolation methods and applications exist in the literature (Dirks et al., 1998; Lin & Chen, 2004; Teegavarapu et al., 2009; Wilk et al., 2006; Basistha et al., 2008; Ruelland et al., 2008; Bargaoui & Chebbi, 2009). Below is presented a tabulated summary of the available methods, including their advantages and limitations.

Table 2.1: Interpolation methods of rainfall data

Method	Advantages	Limitations
Thiessen polygon method	Simple to use.	Not suitable for mountainous areas because of orographic influences (Basistha et al.,

		2008). Inflexibility, Thiessen required every time there is a change in gauge location or network.
Isohyets method	Most accurate approach for determining average precipitation over an area.	Its proper use requires a skilled analyst and careful attention to topographic and other factors that impact on areal variability.
Inverse distance weighted method	Most common method employed regarding the estimation of missing rainfall data.	It is limited in that the powers of weighting functions need to be selected before the interpolation may be performed (Dirks et al., 1998).
Splines method	Best for gently varying surfaces such as elevation, water table heights, or pollution concentrations (Ruelland et al., 2008).	Not appropriate if there are large changes in the surface with a short horizontal distance, because it can overshoot estimated values (Ruelland et al., 2008). The thin-plate methods tend to generate steep gradients in data-poor area leading to compounded errors in the estimation process (Teegavarapu et al., 2009).

		The disadvantage is that the Thin Plate Splines provide a view that is unrealistically smooth (Basistha et al., 2008).
Kriging estimation method	One single observation event is required rather than samples of data in each station (Bargaoui & Chebbi, 2009).	Like other interpolation algorithms, Kriging tends to smooth out local details of the spatial variability of the attribute, leading to overestimation of small values and underestimation of large ones (Basistha et al., 2008, citing Goovaerts, 1997). Kriging has the disadvantage that it can be rather slow for larger data sets (Lin & Chen, 2004).

c) Rainfall duration

The duration of a storm has a direct effect on the volume of runoff from a catchment. Rainfall of any given intensity occurring for longer durations gives rise to more runoff from the catchment. When the intensity is constant and the storm duration is longer, the peak discharge in the stream will rise gradually to a maximum and will continue to rise to the maximum till the end of the storm (Patra, 2008).

d) Rainfall intensity

Rainfall intensity is the depth of rainfall per unit time and it is recorded in the units of millimetres per hour (mm/hr). Reddy (2006) defines rainfall intensity as the rate at which the rainfall is accumulating at any given instant of time. Rainfall intensity is obtained from rain stations that provide continuous records of rainfall data. Chow et al. (1988) report that computations of maximum rainfall depth and intensity give an index of how severe a particular storm is, compared to other storms recorded at the same location, and these computations provide useful data for the design of flow control structures.

The relationship between rainfall intensity and kinetic energy of rainfall has been used to study soil erosion (Lal, 1998; Fornis et al., 2005; Arnaez et al., 2007). Fornis et al. (2005; citing Morgan [1995]) stated that kinetic energy is the most suitable expression of erosivity of rainfall.

e) Soil moisture

Soil moisture conditions at the time of a rainfall event will affect the amount of runoff generated from that rainfall event. Soils experience their high soil moisture condition during rainy seasons or after a rainfall event. If it rains when the soil moisture content is high, then less infiltration of water will occur and more runoff will be generated. Conversely, if the soil moisture condition is low, more rainfall will be absorbed by the soil resulting in less runoff generation.

2.4 Hydrological modelling

Computer-based hydrology models are used extensively for hydrologic predictions and hydrologic system analysis (Chow et al., 1988). A hydrologic model can be defined as a mathematical model representing one or more of the hydrologic processes resulting from precipitation and culminating in catchment runoff. Hydrologic models aid in answering questions about the effect of land management practices on quantity and quality of runoff (Hundecha & Bárdossy, 2004; Saleh & Du, 2004; Linard et al., 2009; Moriasi et al., 2012).

Each model is developed for a specific purpose with certain underlying assumptions. Precautions should be taken that the assumptions of the model are not violated (State of Minnesota Storm-Water Advisory Group, 1997).

2.4.1 Physically based models

A model is physically based if it is derived from equations of mass and energy conservation for the hydrological processes it aims to represent. For most processes these are nonlinear partial differential equations that cannot be solved analytically other than in special cases of restricted interest (Beven et al., 1980). Examples of physically based hydrological models are ACRU, AnnAGNPS, ANSWERS-2000, HSPF, MIKE SHE, and SWAT. These models are subsequently discussed in more detail.

a) Agrohydrological modelling system (ACRU)

The ACRU model is an agrohydrological model developed by the Agricultural Catchments Research Unit of the Department of Agricultural Engineering at the then University of Natal in Pietermaritzburg, South Africa. The model uses daily time step input data such as rainfall and temperature and spatial data is prepared with GIS. ACRU works as a point or lumped model for small catchments and works as a distributed model for large catchments or areas of complex land use and soils. ACRU is not a parameter fitting or optimizing model and variables (rather than optimized parameters) are estimated from physical characteristics of the catchment (Schulze, 1994).

Chetty and Smithers (2005) investigated the use of continuous simulation modelling with ACRU for design flood estimation in South Africa. The results showed that the simulation at quaternary level is not adequate and that further division of quaternary catchment to sub-catchments is necessary to achieve realistic simulated stream flow. The results also indicated that area weighting of the soil and land, and assigned rainfall driver for the sub-catchment gave best stream flow depth. ACRU model has been widely used for assessing eco-hydrological implications runoff harvesting in the headwaters of the Thukela River Basin, South Africa (Winnaar & Jewitt, 2010), for modelling the effect of rainfall variability, land use change and increased reservoir abstractions on surface water resources in Zimbabwe (Mugabe et al., 2011), for assessing the impact of climate change on hydrology of the Thukela River Basin, South Africa (Graham et al., 2011), for assessing hydrological impact due to land use change in three of South African catchments (Warburton et al., 2012).

b) Annualized Agricultural Nonpoint Source Pollution Model (AnnAGNPS)

AnnAGNPS was developed by the USDA Natural Research Service (USDA-ARS) and USDA Natural Resources Conservation Service (USDA-NRCS) to evaluate nonpoint source pollution from agriculturally dominated catchments. The model components or capabilities are hydrology, transport of sediment, nutrients, and pesticides resulting from snowmelt, precipitation, and irrigation. The model has source accounting capability and user interactive programs including TOPAGNPS generating cells and stream network from DEM (Polyakov et al., 2007; Borah & Bera, 2003).

AnnAGNPS was developed from AGNPS model with the following improvements on the original hydrologic concepts:

(i) different approach to catchment discretization and topographic representation of the modeled area;

(ii) introduction of time variant parameters (climatic data); and

(iii) automation of the initial data input procedures by integration of GIS software tools into the modelling system to analyse terrain-dependent parameters and hydrologic characteristics of the drainage system (Baginska et al., 2003).

The model requires topographic, land use, soils and climatic data parameters. Digital Elevation Model (DEM) is preprocessed using GIS processing interface (Kliment et al., 2008) or using TOPAGNPS landscaping analysis tool (Baginska et al., 2003; Sarangia et al., 2007; Hua et al., 2012; Chahor et al., 2014). Land use, crop and agricultural management data are created by field surveys and arial photographs. Physical soil properties such as bulk density, available water capacity and saturated hydraulic conductivity are estimated using Soil Water Characteristics software. Daily climate data required includes daily maximum temperature, daily minimum temperature, precipitation, dew point temperature, percent sky cover, wind direction, wind speed and daily precipitation over period of 2 years.

The following statistical evaluation of AnnAGNPS model in predicting runoff was reported in the literature:

Relative error (*RE)* = 0.01, Nash-Sutcliffe efficiency coefficient (NSE) = 0.94 and Coefficient of determination (R^2) = 0.94 ($p < 0.05$) for monthly time step in the calibration period; *RE* = −0.06, *NSE* = 0.93 and R^2 = 0.93 ($p < 0.05$) for monthly time step in the validation period (Hua et al., 2012); and

NSE_m= 0.75 and NSE_s= 0.79, respectively, for monthly (m) and seasonal (s) time step as well as $E1_m$= 0.58, $E1_s$= 0.60 and $PBIAS_m$= −2.65, $PBIAS_s$= −2.38. R^2_m = 0.79 and R^2_s = 0.81 (Chahor et al., 2014).

c) Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS-2000)

ANSWERS-2000 is a continuous simulation, distributed model capable of evaluating daily water balance, infiltration, runoff and surface water routing, drainage, river routing, ET, sediment transport, nitrogen and phosphorous transformations, nutrient losses through uptake, runoff, and sediment. It was developed by Purdue University and Virginia Polytechnic Institute and State University (Borah & Bera, 2003). ANSWERS model has been used in various studies to simulate runoff volumes (Connolly et al., 1997; Singh et al., 2006) and sediment yield (Walling et al., 2003; Ahmadi et al., 2006).

d) Hydrological Simulation Program in FORTRAN (HSPF)

HSPF includes components that predict runoff and water quality constituents on land areas, movement of water and constituents in stream channels and mixed reservoirs. The model is part of the United States Environmental Protection Agency (USEPA) BASINS modelling systems with user interface and ArcViewGIS platform (Borah & Bera, 2003).

The application of HSPF to a catchment requires physical data (topographic, land use) and climate data (precipitation, temperature, average wind speed, average humidity, average solar radiation, daily potential evaporation (Chung & Lee, 2009). The model was applied in number of studies to simulate water quantity and water quality with varying degrees of success. HSPF reproduced monthly runoff with correlation coefficients ranging from 0.87 to 0.89 during the calibration (Im et al. 2003). Xei & Lian (2013) reported Nash-Sutcliffe efficiency coefficient between 0.58 and 0.88 from HSPF application to the Illinois River Basin. Statistical evaluation of HSPF model gave Nash-Sutcliffe efficiency coefficient ranging between 0.70 and 0.84 for daily and monthly calibration period respectively, and ranging between 0.84 and 0.86 for daily and monthly validation period respectively, as reported by Fonseca et al. (2014).

e) MIKE SHE

MIKE SHE model components are interception – ET, overland channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, dual porosity and irrigation. The model has user interface with pre- and post-processing, GIS, and UNIRAS for graphical presentation. After the mid-1980s MIKE SHE was further developed and extended by DHI Water and Environment (Borah & Bera, 2003).

MIKE SHE model has been widely used and applied in various parts of the world assess water quantity and water quality (Doummar et al., 2012). MIKE SHE has also been applied to quantify hydrologic response to land use change and climate variability (Thompson et al., 2004; McMichael et al., 2005; Sahoo et al., 2006; Zhang et al., 2008).

f) Storm Water Management Model (SWMM)

SWMM was developed by the Environmental Protection Authority (EPA) in 1971. It simulates single-event or continuous urban runoff and the water quality associated with the runoff and in the combined sewer system. To simulate flow quantity, the water storage balance is used for the flow from the land surface and the equations of continuity and motion are used for channel flow prediction (Rattanaviwatpong, 2001). The processes included are rainfall, snowmelt, surface runoff, subsurface runoff, flow routing, storage, and treatment of flows (Zaghloul & Kiefa, 2001; Sharifan et al., 2010; Ouyang et al., 2012; Burger et al., 2014). The pollutants that are simulated in the storm water runoff are, with regard to water quality, phosphates, nitrates, suspended solids and other pollutants.

g) Soil and Water Assessment Tool (SWAT)

SWAT components include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing and water transfer and it is part of the USEPA BASINS modelling system with user interface and ArcViewGIS platform. It is a product of the USDA-ARS.

The SWAT modelling system allows the user to estimate water quantities available for extraction at any point and time and represents the dynamics of soil-water, which controls plant growth and chemical cycling (Schattenberg, 2011). In SWAT model the catchment is divided into multiple sub-catchments which are further subdivided into hydrologic response units (HRUs) that consist of homogenous land use, management, and soil characteristics. The HRUs represent percentages of the sub-catchment area and are not identified spatially within the SWAT simulation. Alternatively, a catchment can be subdivided into only sub-catchments that are characterized by dominant land use, soil type, and management (Winchell et al., 2007; Gassman et al., 2007).

The SWAT model has been widely used and applied worldwide to address water quantity and water quality issues (Arnold & Allen, 1996; Butts et al., 2004; Bouraoui et al., 2005; Chaplot et al., 2005; Kim & Pachepsky, 2010; Oeurng et al., 2011; Mutenyo et al., 2013; Molina-Navarro et al., 2014). SWAT has also been applied in South Africa to model effect of land use change on hydrology of the catchment (Govender & Everson, 2005; Welderufael et al., 2013). Gassman et al. (2007) grouped SWAT applications under broad categories such as hydrologic only, hydrologic and pollutant loss or pollutant loss only to assess model efficiency in the reported studies.

2.4.2 Model selection

A hydrological model is selected based on its capacity to simulate the hydrology and water quality processes in the catchment and give accurate results compared to those measured to check the effectiveness of the model (Rattanaviwatpong, 2001). Given the wide range of hydrological models that are available, the choice of a model for a particular problem is never a simple one, and will inevitably be based on economic constraints, data availability and personal preferences as well as purely hydrological considerations (Beven et al., 1980).

Beven (2001) suggested the following procedure on choosing a model based on considerations regarding the function of possible modelling structures:

- Prepare a list of the models under consideration. This list may have two parts: those models that are readily available, and those that might be considered for a project if the investment of time (and money) appeared to be worthwhile.

- Prepare a list of variables predicted by each model as well as those variables required. Decide whether the model under consideration will produce the outputs needed to meet the aims of a particular project. For instance, if one is interested in the rise in water table in valley bottoms due to deforestation, a model predicting the lumped response of the catchment may not fulfil the needs of the project. If, however, one is only interested in predicting the discharge response of a catchment for real-time flood forecasting, then it may not be necessary to choose a distributed modelling strategy.

- Prepare a list of the assumptions made by the model. Are the assumptions likely to be limiting in terms of what one knows about the response of the catchment one is interested in? Unfortunately the answer is likely to be affirmative for all models, so this assessment will generally be a relative one, or at best a screen to reject those models that are obviously based on incorrect representations of the catchment processes.

- Make a list of the inputs required by the model, for specification of the flow domain, for the specification of the boundary and initial conditions and for the specification of the parameter value. Decide whether all the information required can be provided within the time and cost constraints of a specific project.

- Determine whether there are any models left on one's list. If not, review the three previous steps, relaxing the criteria employed. If predictions are really required for an application, one model at least will need to be retained at this stage.

2.4.3 Evaluation of model performance

Successful model evaluation comprises both operational and scientific examination (Willmott et al., 1985). Operational examination evaluates a specific model's precision and accuracy. Accuracy refers to the extent to which model-predicted values approach a corresponding set of measured observations (Loague & Green, 1991; Legates & McCabe, 1999). Evaluation of model performance should include both statistical criteria and graphical displays. Moriasi et al. (2007) recommend the use of both graphical techniques and quantitative statistics in model evaluation. This combined assessment approach can be useful for making comparative evaluations of model performance between alternative/competing models (Loague & Green, 1991).

a) Statistical measures

Statistical analysis has been outlined and used in a number of studies to evaluate model performance (e.g. Willmott et al., 1985; Loague & Green, 1991; Legates & McCabe, 1999; Borah & Bera, 2003; Chanasyk et al., 2003; Saleh & Du, 2004; Romanowicz et al., 2005; Wang & Melesse, 2005; Moriasi et al., 2007; Srinivasan et al., 2010; Moriasi et al., 2012, Arnold et al., 2012). Table 3 gives some of the hydrological evaluation indices (adopted from Romanowicz et al., 2005).

Table 2.2: The hydrological evaluation indices

Definition	Coefficients (Reference)	Comments
$NSE = 1 - \frac{\sum (O_i - P_i)^2}{\sum (O_i - \overline{O})^2}$	Nash-Sutcliffe (Nash & Sutcliffe, 1970)	The optimal statistical value occurs when the value does reach 1
$MAE = N^{-1}\sum_{i=1}^{n} \lvert O_i - P_i \rvert$	Mean absolute error (Legates & McCabe, 1999)	The optimal statistical value is close to 0
$RMSE = \left(\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n} \right)$	Root mean square error (Moriasi et al. 2007)	The optimal statistical value is close to 0
$RMS = \left(\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n} \right) X100$	Root mean square (Loague & Green, 1991)	In %; the optimal statistical value is close to 0

$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i}$	Coefficient of residual mass (Loague & Green, 1991)	This indicator identifies when the model overestimates (negative values) or underestimates (positive values) the values

O_i, observed value; $\overline{O}$, mean observed; P_i, simulated value.

b) Graphical displays

Different graphical techniques are used to evaluate model performance visually in addition to the statistical indices generated. The most common ones are hydrographs and per cent exceedance probability curves (Moriasi et al., 2007), matching the observed and predicted or simulated results throughout the calibration and validation process. It would be ideal to have graphical display where observed and predicted results are coincident (Loague & Green, 1991). Hydrographs help in identifying model bias (ASCE, 1993; cited by Moriasi et al., 2007) and show peak flows and duration of storms. Per cent exceedance probability curves, which often are daily flow duration curves, can illustrate how well the model reproduces the frequency of measured daily flows throughout the calibration and validation periods (Van Liew et al., 2007; cited by Moriasi et al., 2007).

c) Model evaluation guidelines

Prior to the study by Moriasi et al. (2007), there was no guidance to facilitate model evaluation in terms of the accuracy of simulated data compared to measured flow and constituent values. As a result the aforementioned study was conducted to develop guidelines for model evaluation through reported statistical results in the literature. The objectives of the study by Moriasi et al. were threefold, namely to:

- Determine recommended model evaluation techniques (statistical and graphical)

- Review reported ranges of values and corresponding performance ratings for the recommended statistics
- Establish guidelines for model evaluation based on the review results and project-specific considerations

All of these objectives focused on simulation of stream flow and transport of sediment and nutrients. The study furthermore focused on the following evaluation statistics: Nash - Sutcliffe efficiency (NSE), Percent bias (PBIAS), and RMSE – observations standard deviation ratio (RSR) at the calibration and validation stage of modelling. Table 2.3 shows the performance ratings for recommended statistics.

Table 2.3: General performance ratings for recommended statistics for a monthly time step (Moriasi et al., 2007).

			PBIAS (%)		
Performance rating	RSR	NSE	Stream flow	Sediment	N,P
Very good	0.00 < RSR < 0.50	0.75 < NSE < 1.00	PBIAS < ±10	PBIAS < ±15	PBIAS< ±25
Good	0.50 < RSR < 0.60	0.65 < NSE < 0.75	±10 < PBIAS < ±15	±15 < PBIAS < ±30	±25 < PBIAS < ±40
Satisfactory	0.60 < RSR < 0.70	0.50 < NSE < 0.65	±15 < PBIAS < ±25	±30 < PBIAS < ±55	±40 < PBIAS < ±70
Unsatisfactory	RSR > 0.70	NSE < 0.50	PBIAS > ±25	PBIAS > ±55	PBIAS > ±70

CHAPTER 3: MATERIAL AND METHODS

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3.1 Introduction

ArcSWAT model input data includes digital elevation model (DEM), land use, soil type, climate data and observed stream flow data. After the model was set up, a warm-up simulation was run. A sensitivity analysis was performed to identify sensitive parameters that may influence the model's simulation results. The parameters are ranked according to the degree of their sensitivity to the model output and the auto-calibration tool was run with Parasol to improve the accuracy of the model. Finally, the model was evaluated against acceptable guidelines for monthly time step.

3.2 Description of the Modder River Basin Area

The whole Modder River Basin is a large basin with a total area of 17 366 km^2. It is divided into three sub-basins, namely the Upper Modder, the Middle Modder and the Lower Modder. The study site is located within the Upper Orange Water Management Area to the east of the city of Bloemfontein (located in the Free State Province in central South Africa). The water supply to the middle and lower reaches of the Modder River is stabilized by the Rustfontein and Mockes dams in the east and the Krugersdrift Dam in the west of the city of Bloemfontein.

The study site, C52B, is a quaternary catchment (sub-catchment) within the C52 tertiary catchment (Fig. 3.1). The total area of the study site is estimated to be 949 km^2. The Mean Annual Evaporation (MAE) of C52B sub-catchment is 1570 mm with a Mean Annual Precipitation (MAP) of 534 mm and with Mean Annual Runoff (MAR) of 39 x 10^6 m^3 (Midgley et al. 1994). The climate of the area is semi-arid.

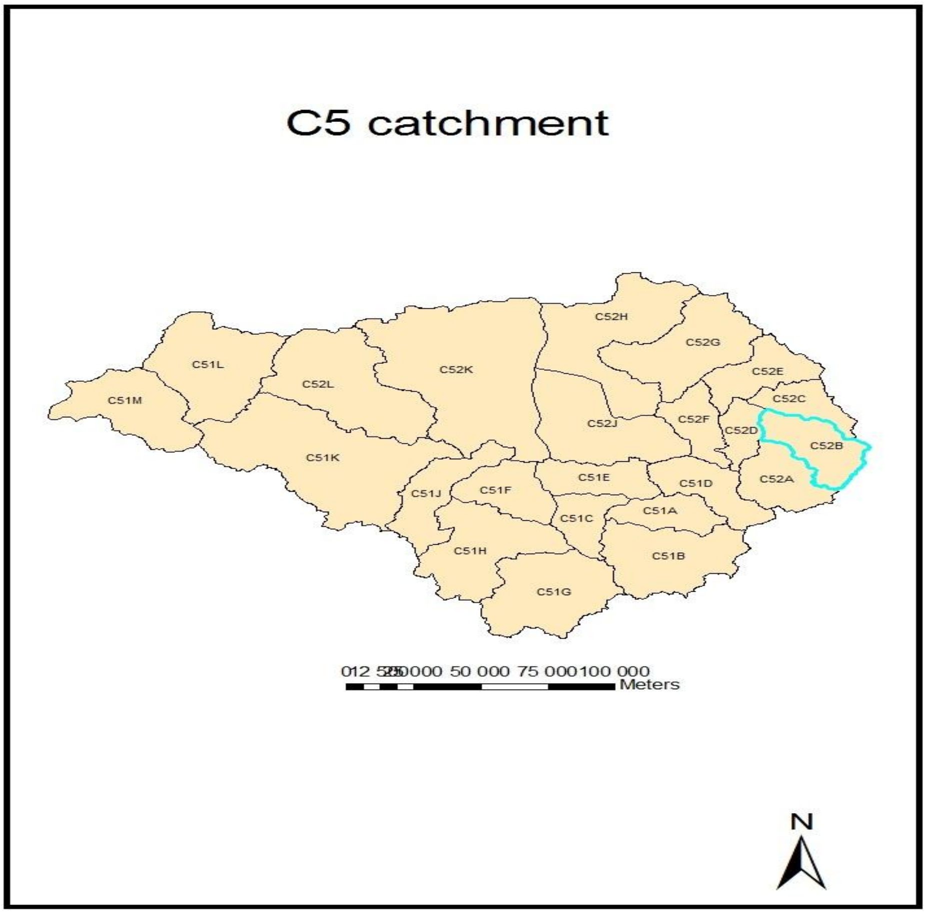


Figure 3.1: Map of C5 secondary catchment showing the quaternary catchments and the study site (C52B) in the Upper Modder River Basin.

3.3 Delineation of the Catchment

The SWAT model can be applied with different spatial discretization schemes, but most users apply it in a semi-distributed way which is supported by a user-friendly ArcGIS interface (DiLuzio et al., 2002; DiLuzio et al., 2004). The catchment was delineated by following the five steps in ArcSWAT and which includes DEM set-up, stream definition, outlet and inlet definition, and calculation of sub-basin parameters. The study area was manually delineated by drawing the polygon (masking) around the study area. In the SWAT model, sub-basins are calculated as contributing area to an individual stream channel. Threshold value of 930 hectares was used and 24 sub-basins were created (Fig. 3.2).

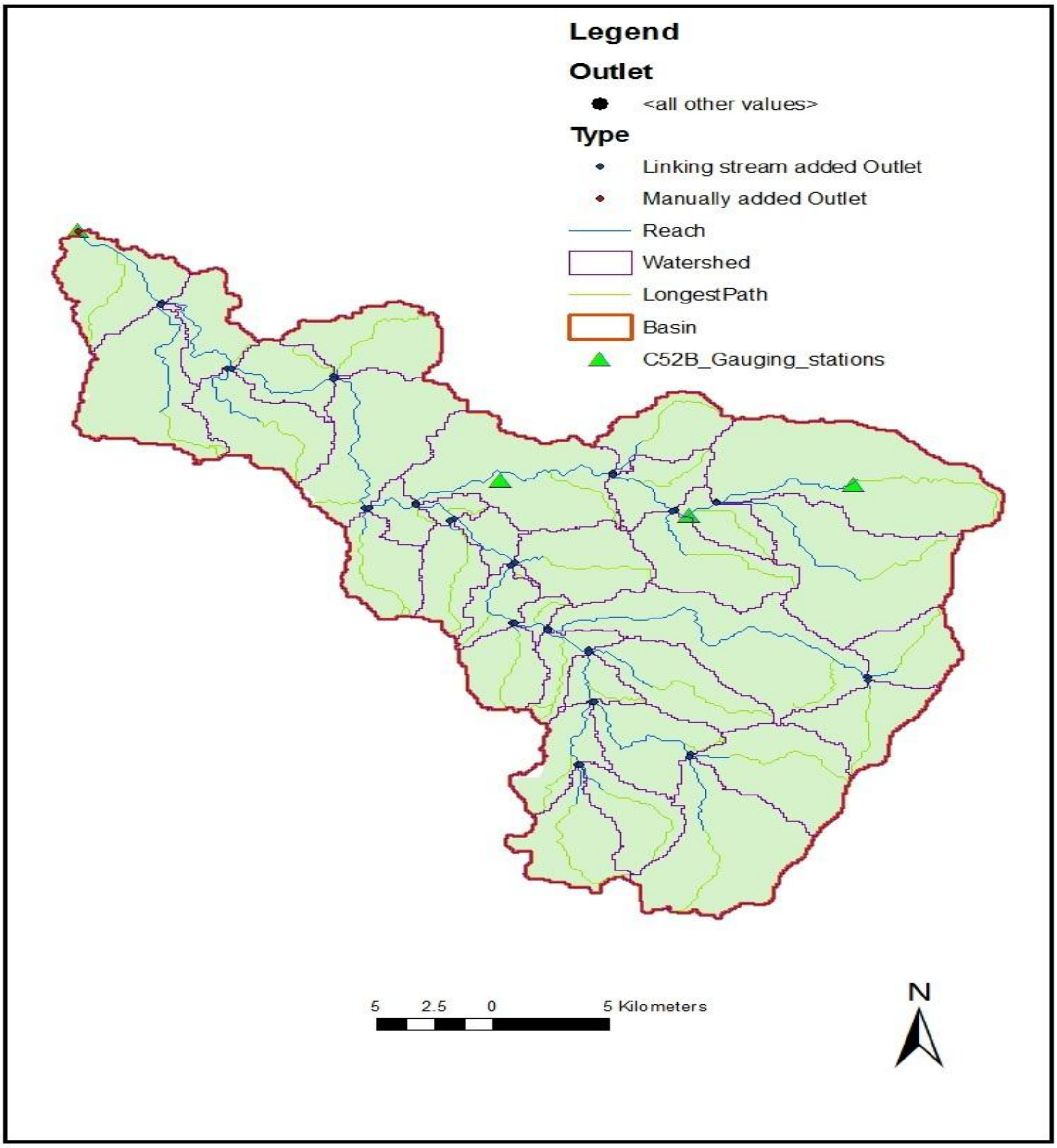


Fig. 3.2: Delineation of sub-catchments (sub-basins) using SWAT model.

Stream flow network was edited by manually adding an outlet to the catchment. Adding an outlet at the known location of a stream flow gauging station is useful for the comparison of the predicted and observed stream flow data. The added outlet had sufficient stream flow data available from 1993 – 2010 (Fig. 3.3).

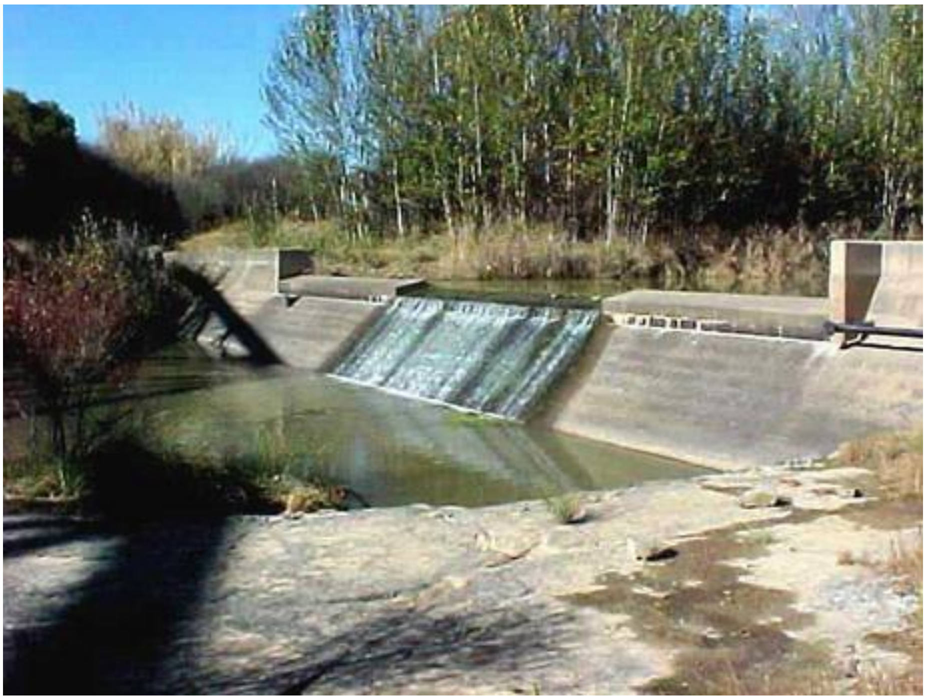
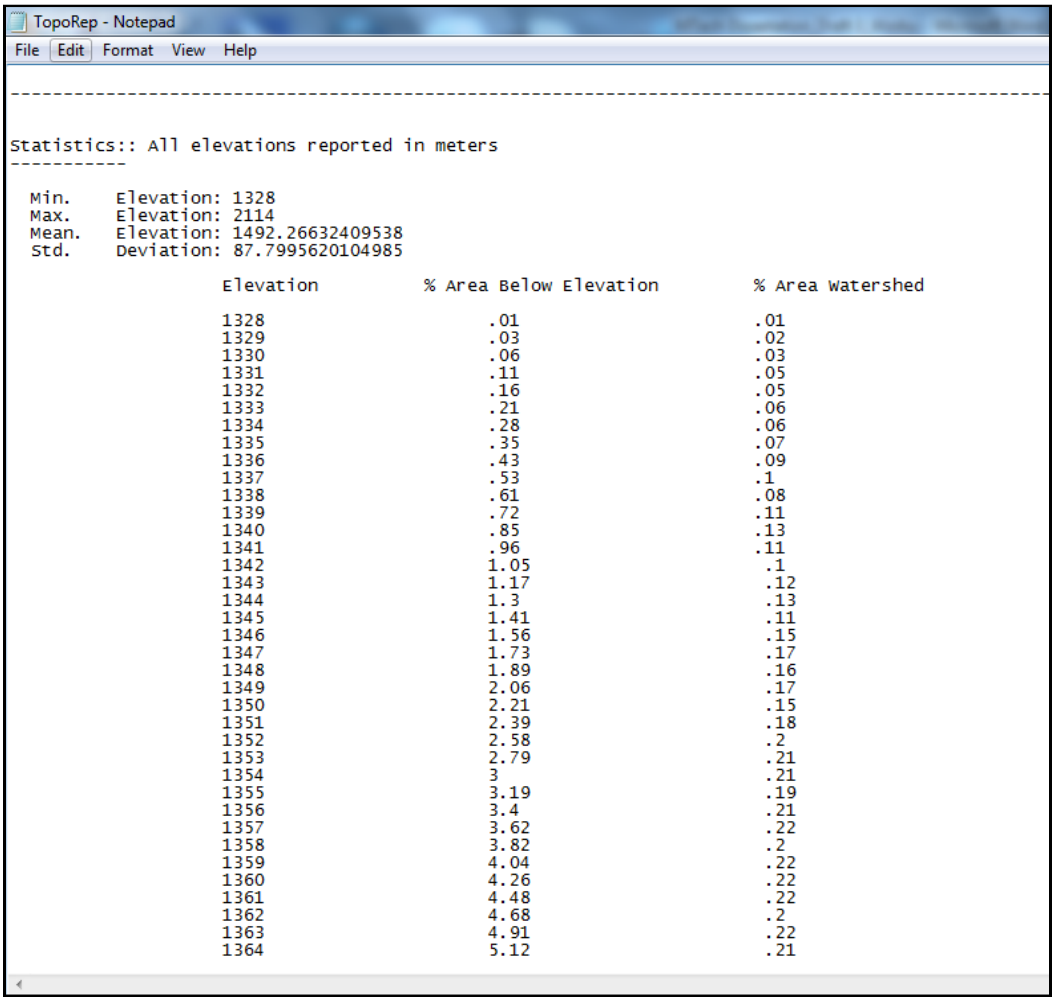


Fig. 3.3: Gauging Station C5H003 with available data from 1993 – 2010 (Source: http://www.dwa.gov.za/Hydrology/CGI-BIN/HIS/CGIHis.exe/Photo?Station=C5H003).

Catchment delineation was completed by calculating sub-basin parameters. The sub-basin parameters calculated were geomorphic parameters for each sub-basin and relative stream reach. Fig. 3.4 below is a topographic report of the catchment providing statistical summary and distribution of discrete land surface elevations in the catchment and all the sub-basin catchments.



TopoRep - Notepad

Statistics:: All elevations reported in meters

Min.	Elevation:	1328
Max.	Elevation:	2114
Mean.	Elevation:	1492.26632409538
Std.	Deviation:	87.7995620104985

Elevation	% Area Below Elevation	% Area Watershed
1328	.01	.01
1329	.03	.02
1330	.06	.03
1331	.11	.05
1332	.16	.05
1333	.21	.06
1334	.28	.06
1335	.35	.07
1336	.43	.09
1337	.53	.1
1338	.61	.08
1339	.72	.11
1340	.85	.13
1341	.96	.11
1342	1.05	.1
1343	1.17	.12
1344	1.3	.13
1345	1.41	.11
1346	1.56	.15
1347	1.73	.17
1348	1.89	.16
1349	2.06	.17
1350	2.21	.15
1351	2.39	.18
1352	2.58	.2
1353	2.79	.21
1354	3	.21
1355	3.19	.19
1356	3.4	.21
1357	3.62	.22
1358	3.82	.2
1359	4.04	.22
1360	4.26	.22
1361	4.48	.22
1362	4.68	.2
1363	4.91	.22
1364	5.12	.21

Fig. 3.4: Catchment topographic report as generated by SWAT.

3.4 Input data

Depending on the scale of the project, the SWAT model, like any other hydrological model, requires large amounts of data. Data preparation is the most important aspect and was the most time-consuming process in this study.

3.4.1 Digital Elevation Model (DEM)

The projected coordinate system was WGS_1984_Albers and the geographic coordinate system was GCS_WGS_1984. The shape and size of a geographic coordinate system's (GCS) surface was defined by a spheroid/ellipsoid that was designed using World Geodetic System of 1984 (WGS 1984 or WGS84). The projected coordinated system is defined on the flat, two-dimensional surface and is based on the geographic coordinate system. The Albers Equal Area Conic projection system is a conical projection that uses two standard parallels to reduce some distortion of a projection with one standard parallel (ERSI, 2004). The Digital Elevation Model (Figure 3.5) was delineated from the Digital Elevation Model of C5 secondary catchment.

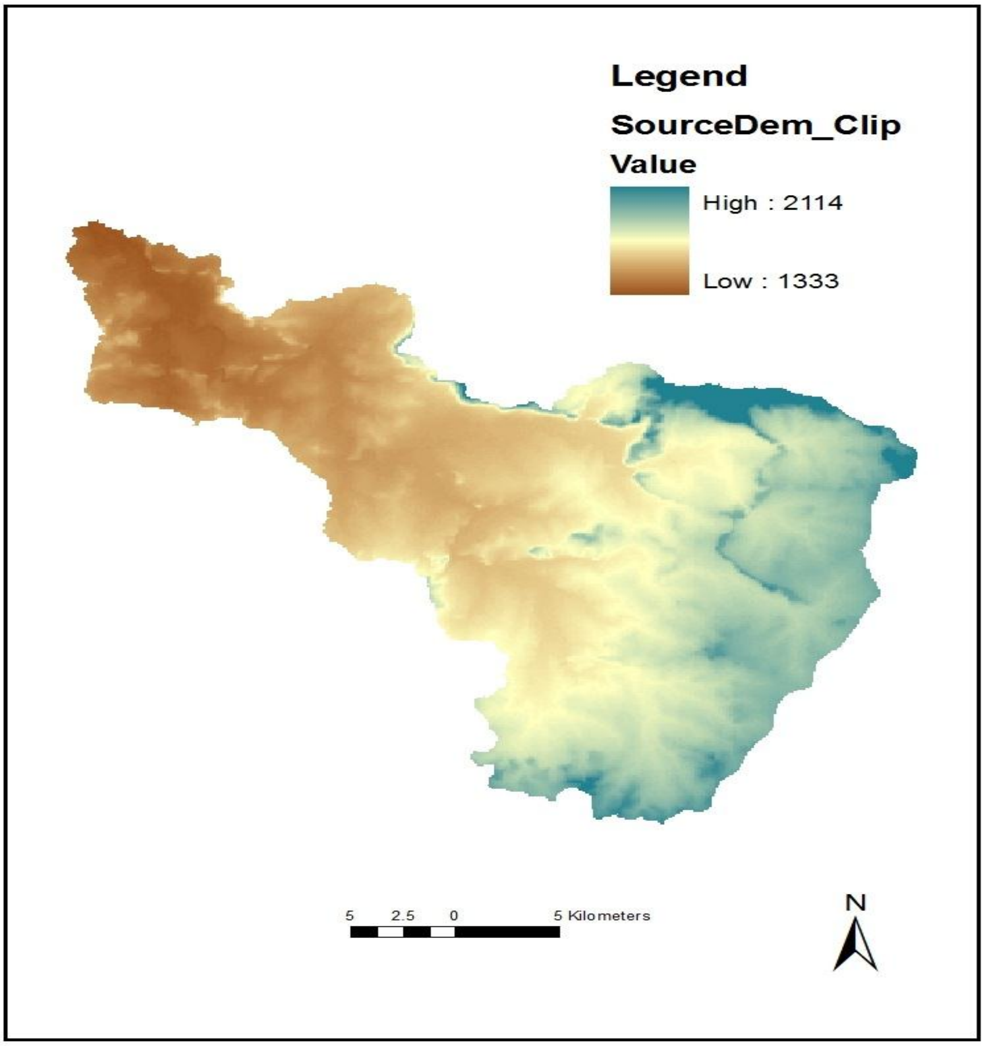


Fig. 3.5: Digital Elevation Model (DEM) of the study area.

3.4.2 Climate

The annual average maximum and minimum temperatures are 23°C and 7°C and the mean annual rainfall is 534 mm.

3.4.2.1 Daily data

Daily weather data, such as measured precipitation, wind speed, maximum temperature and minimum temperature data for an 18-year period (1993 to 2010) were obtained from the South African Weather Services (SAWS). Daily weather data was used by the SWAT Weather Generator to generate various weather parameters to patch areas where data was missing.

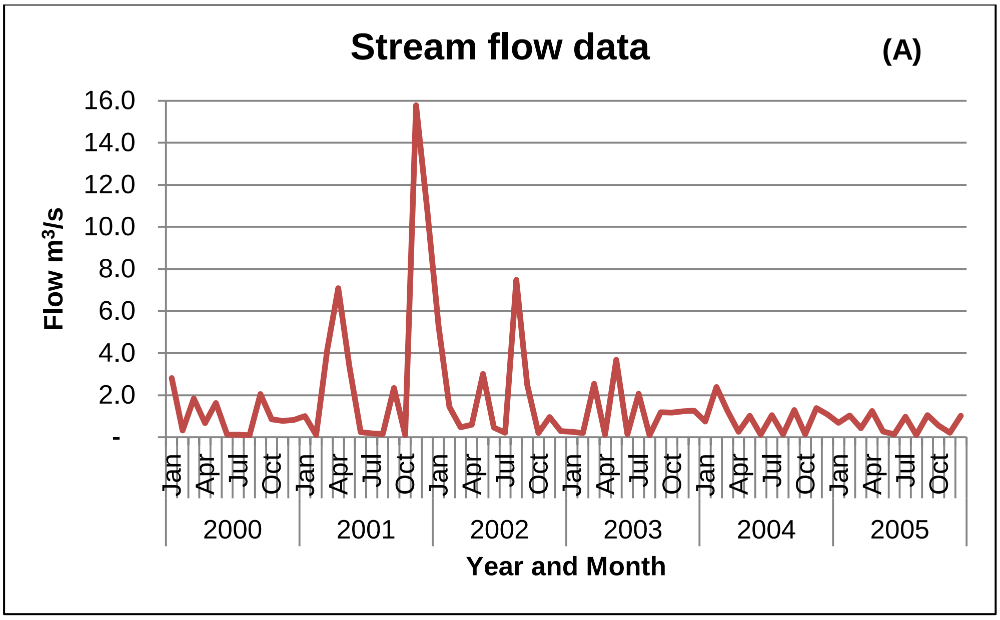
Table 3.1: Weather and Rainfall Stations

Name	Start date	End date	Years
Thaba Nchu*	01/01/1993	31/12/2010	18
Cliff	01/01/1993	31/12/2010	18
Bloem	01/01/1993	31/12/2010	18

* Rainfall data only

3.4.2.2 Monthly data

Monthly stream flow data for the C5H003 gauging station were recorded by the Department of Water Affairs (DWA). For this gauging station, data for the six-year period of 2000 to 2005 were used for calibration, and data from 2006 to 2009 were used for validation (Fig. 3.7: A & B).



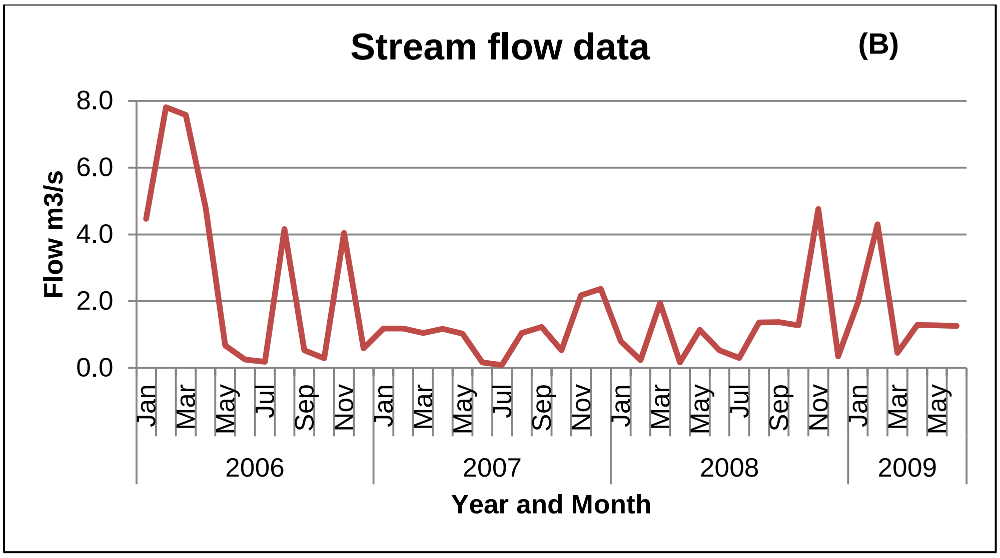


Fig. 3.7 (A & B): Observed stream flow hydrograph based on data at gauging station C5H003.

3.5 Statistics for model evaluation

The NSE (Equation 1), Pbias (Equation 2), RSR (Equation 3) and R^2 (Equation 4), were calculated to evaluate the SWAT model's performance as shown below;

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

$$Pbias = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) * 100}{\sum_{i=1}^{n} \left(Y_i^{obs} \right)} \right] \tag{2}$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \right]} \tag{3}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)\left(Y_i^{sim} - Y^{mean} \right)}{\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \sqrt{\sum_{i=1}^{n} \left(Y_i^{sim} - Y^{mean} \right)^2}} \right)^2 \tag{4}$$

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 and simulated data for the constituent being evaluated, and n is the total number of observations during the simulated period.

The efficiency of Nash and Sutcliffe (NSE) as proposed by Nash and Sutcliffe (1970) is (Equation (1)) normalized by the variance of the observed values during the period under investigation (Krause et al., 2005). The larger values in a time series are strongly overestimated whereas lower values are neglected (Legates & McCabe, 1999; cited by Krause et al., 2005). RSR is calculated as the ratio of the RMSE and standard deviation and optimal value is 0 (Moriasi et al., 2007). Percent bias (Pbias) measures the average tendency of the simulated data to be larger or smaller than their observed data (Moriasi et al., 2007).

CHAPTER 4: RESULTS AND DISCUSSION

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4.1 Model set-up

Original land use data obtained from a land use map of 2000 was reclassified to fit the syntax and naming used by the ArcSWAT hydrological model. Fig. 4.1 is a digital map of the reclassified land use of the study area.

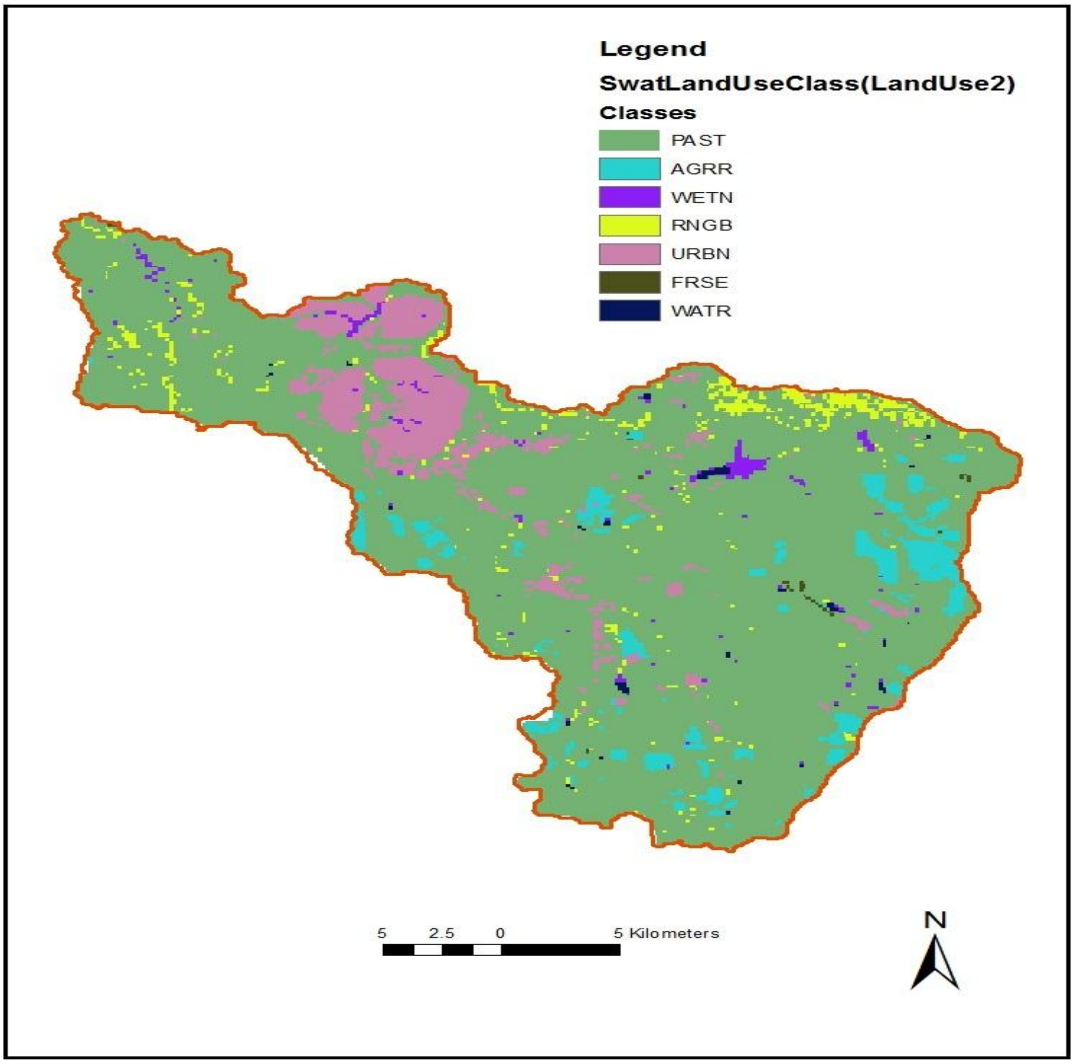


Fig. 4.1: Land-use map of the study area.

The reclassified land use and percentage cover area are presented in Table 4.1 below. Pasture land covers 89.07% of the total area, urban area covers 7.61% of the total, agricultural land covers 1.98% and other land uses cover less than 2% of the total area.

Table 4.1: SWAT land use types and percentage area for the study site.

Reclassified land use	Area (%)
PAST (Pasture land)	89.07
URBN (Urban land)	7.61
RNG (Range land)	1.19
WETN (Wet land)	0.15
AGRR (Agricultural land)	1.98

Fig. 4.2 shows part of the HRU distribution report which provides a detailed description of the distribution of the land, soil and slope classes after application of thresholds for the catchment and all the sub-basins. The total drainage area draining to the outlet is 699.46 km^2.

```
SWAT   model  simulation    Date: 2012/10/05 12:00:00 AM    Time: 00:00:00
MULTIPLE HRUs  LandUse/Soil/Slope OPTION              THRESHOLDS : 10 / 0 / 20 [%]
Number of HRUs: 65
Number of Subbasins: 24

                                                            Area [ha]         Area[acres]
Watershed                                                  69946.0000         172840.0633

                                                            Area [ha]         Area[acres] %Wat.Area
LANDUSE:
                                       Pasture --> PAST    62298.9013         153943.7001     89.07
                                   Residential --> URBN     5320.3993          13146.9727      7.61
                                   Range-Brush --> RNGB      829.2400           2049.0935      1.19
                         Wetlands-Non-Forested --> WETN      103.0864            254.7315      0.15
                    Agricultural Land-Row Crops --> AGRR     1394.3730           3445.5655      1.99

SOILS:
                                              Dc 17        69946.0000         172840.0633    100.00

SLOPE:
                                                    0-3    48383.6183         119558.3401     69.17
                                                    3-5    12181.1552          30100.2436     17.42
                                                 5-9999     9381.2264          23181.4796     13.41

                                                            Area [ha]         Area[acres] %Wat.Area %Sub.Area
SUBBASIN #                                            1        50.0000            123.5525      0.07
LANDUSE:
                                       Pasture --> PAST        47.2771            116.8241      0.07     94.55
SOILS:
                                              Dc 17            47.2771            116.8241      0.07     94.55
SLOPE:
                                                    0-3        29.0110             71.6875      0.04     58.02
                                                    3-5        18.2662             45.1366      0.03     36.53
HRUs
 1                      Pasture --> PAST/BELGRADE/0-3          29.0110             71.6875      0.04     58.02    1
 2                      Pasture --> PAST/BELGRADE/3-5          18.2662             45.1366      0.03     36.53    2

                                                            Area [ha]         Area[acres] %Wat.Area %Sub.Area
SUBBASIN #                                            2      2231.0000           5512.9126      3.19
LANDUSE:
```

Fig. 4.2: HRU distribution report as generated by SWAT for the study area.

The digital elevation model and the soil map (see section 3.4.1, Fig. 3.5) and the land use (Fig. 4.1) were used to delineate sub-basins and HRUs. In ArcSWAT, the Multiple HRUs command was used to create HRUs for each sub-basin in the hydrologic analysis. The threshold values used to create HRUs are 10% for land use, 0% for soil and 20% for slope in the HRU definition. The threshold percentage of zero for the soil was used because the soil type of the sub-basin C52B is dominated by Dc 17 (Fig. 4.3). Therefore, in this case, an HRU would not be created for land use type which has less than 10% surface coverage as well as for a slope with less than 20% surface coverage from the identified slope ranges. Thus, each HRU created in a sub-basin has a known area but is not spatially located in the sub-basin.

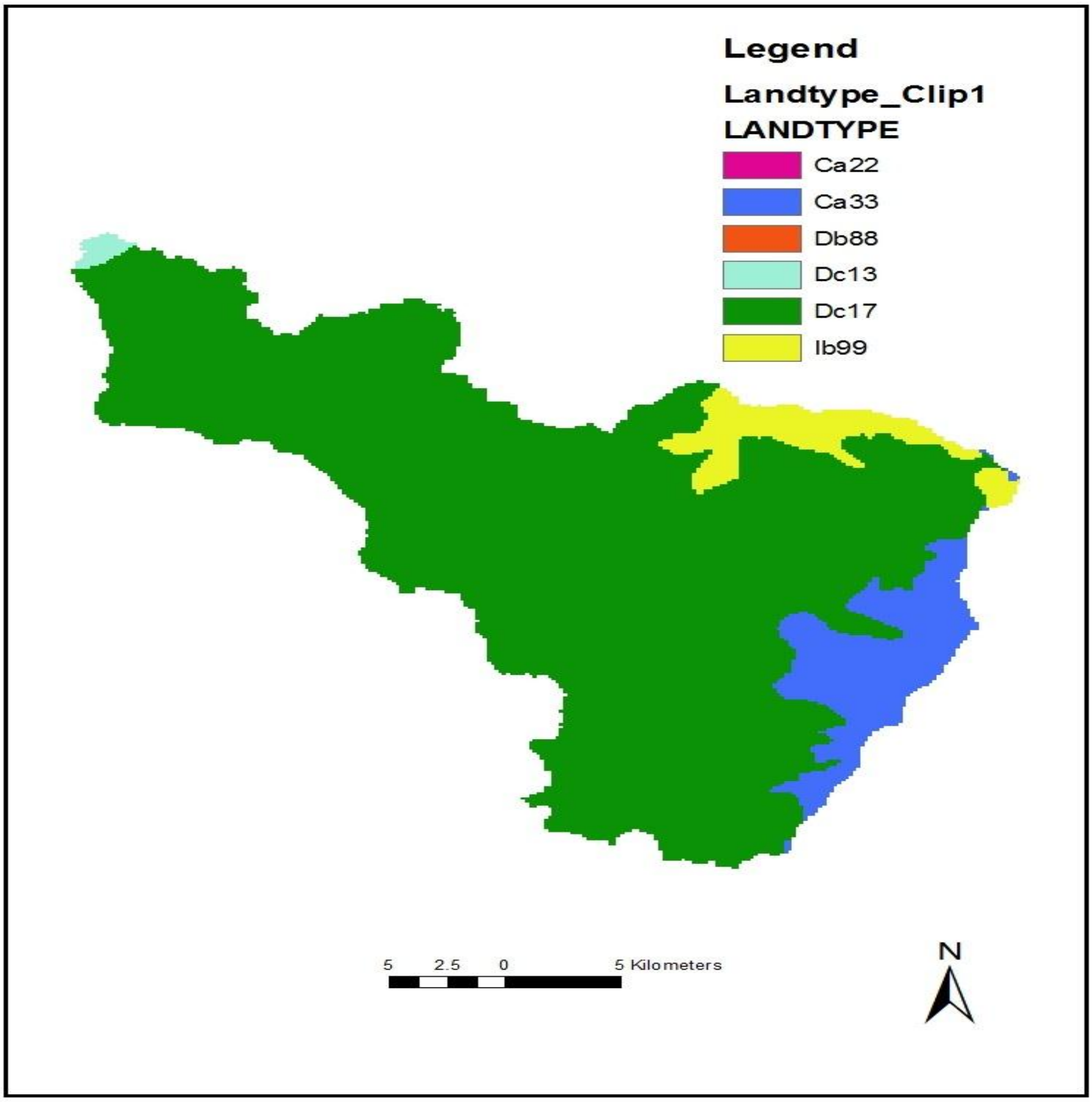


Fig. 4.3: Land-type map of the study area.

Table 4.2 shows the average monthly and annual temperature and precipitation for the study area, i.e. C52B. The average values were calculated from long-term records of 600 monthly values for temperature and precipitation.

Table 4.2: Average monthly and annual temperature (T) and precipitation (P) for C52B.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
T (°C)	21.5	21	19	15	11.5	7.7	8.1	10	14	17	19	20.5	15.4
P (mm)	78	75	79	47	22	9	14	9	27	47	67	60	534

The study area (C52B) is classified as semi-arid according to the Köppen-Geiger climate classification system. The map of the Köppen-Geiger climate-type for Africa (Fig. 3.6) shows that C52B falls under the area which is classified as Cwa, meaning the temperature of the hottest month is greater than 10°C, with dry winters and hot summers (Peel et al., 2007).

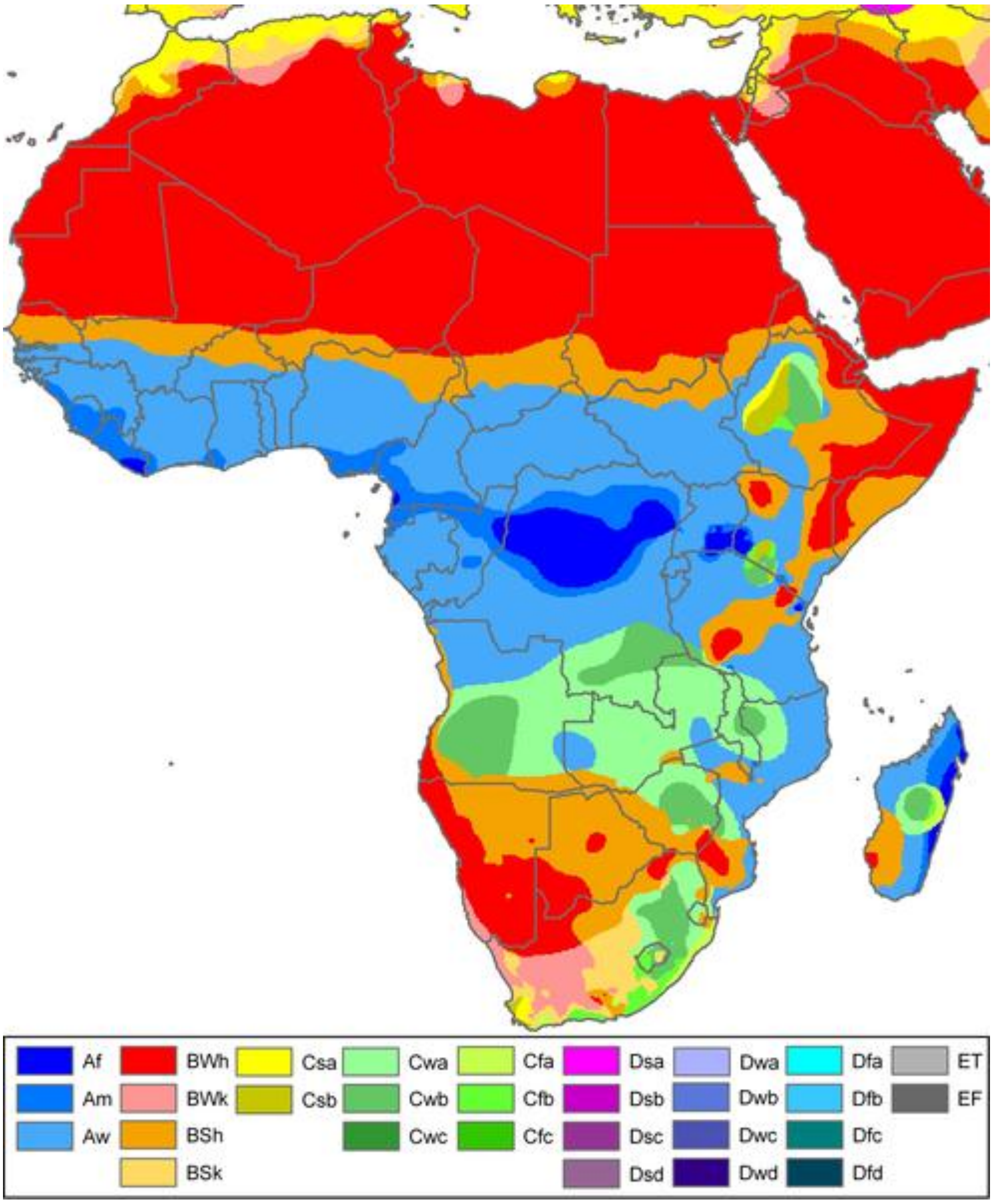


Fig. 4.4: Köppen-Geiger climate-type map of Africa (Source: M.C. Peel et al., 2007).

Long-term statistical data (Table 4.3 and 4.4) for the weather generator were calculated with monthly average precipitation and maximum and minimum temperature using pcpSTAT and dewpoint programs (Liersch, 2003a; Liersch 2003b), while monthly-average wind speed, average solar radiation, standard deviation for minimum and maximum temperature were calculated manually. Fifty years of data was processed for this purpose for a period of 1950 to 1999. The data was used by the SWAT Weather Generator to generate climatic data or fill in the gaps in measured records.

Table 4.3: Description of Weather Generator input data.

Name	Definition
TITLE	Name of the station
WLATITUDE	latitude and longitude in degrees of the weather station
WELEV	the elevation of the weather station in meters above mean sea level
RAIN_YRS	number of years used to calculate the maximum half-hour rainfall
TMPMX	average or mean daily maximum air temperature (in °C)
TMPMN	average or mean daily minimum air temperature in month (°C)
TMPSTDMX	standard deviation for daily maximum air temperature in month (°C)
TMPSTDMN	standard deviation for daily minimum air temperature (in °C)
PCPMM(mon)	average or mean total monthly precipitation
PCPSTD(mon)	standard deviation for daily precipitation in month
PCPSKW(mon)	skew coefficient for daily precipitation in month
PR_W1(mon)	probability of a wet day following a dry day
PR_W2(mon)	probability of a wet day following a wet day
PCPD(mon)	average number of days of precipitation in month
SOLARAV	average daily solar radiation in month
DEWPT	average daily dew point temperature for each month
WINDAV (optional)	average daily wind speed in month

Table 4.4: Weather Generator input data.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMP	MX	14	14	12	7	3	-0.6	-0.9	1	5	9	11	13
	MN	29	28	26	23	20	16	17	19	23	25	27	28
TMPSTD	MX	3.6	3.5	3.4	3.5	3.3	3.1	2.9	3.6	4.2	4.0	3.7	3.4
	MN	2.4	2.4	2.7	3.4	3.1	2.9	2.8	3.6	3.9	3.73	3.1	2.6
PCP	MM	78	75	79	47	22	9	14	9	27	47	67	60
	STD	7.2	6.9	7.1	5.1	3.5	2.2	3	1.9	4.9	5.3	6.5	5.8
	SKW	4.6	4.2	3.8	4.8	6.8	10.5	9	8.4	7.7	5.6	4.1	5.1
	W1	0.17	0.20	0.15	0.11	0.05	0.03	0.03	0.03	0.04	0.11	0.15	0.14
	W2	0.38	0.39	0.38	0.32	0.21	0.28	0.23	0.25	0.29	0.35	0.36	0.38
	D	7.08	7.36	6.40	4.78	2.04	1.20	1.26	1.36	1.84	4.52	6.00	5.90
SOLAR	AV	26	23	20	17	14	13	13	16	19	22	25	27
DEW	PT	16	15	14	10	7	2	3	4	7	10	12	14
WIND	AV	3.1	2.4	1.8	1.2	0.8	0.8	0.8	1.3	1.8	2.8	3.2	3.3

Model calibration involves optimization of the model parameters to acquire the best fit between observed and simulated data. The SWAT model contains many parameters which cannot be adjusted all at the same time. Therefore the calibration procedure was performed by selecting most sensitive parameters to stream flow, which in most cases are soil parameters and curve number (CN) (Lenhart et al., 2002). Table 4.2 gives the top ten most sensitive parameters. Soil evaporation and curve number are the most sensitive parameters in this particular study. A similar order of parameter rankings in sensitivity analysis were also reported by Welderufael et al. (2013).

Minimum and maximum relevant input variables were specified based on the recommendations in the development of the SWAT model as well as by parameter values obtained during the set-up process of the SWAT model. Initial running of the model was performed with those default parameters values and were later adjusted at the calibration stage.

Table 4.5: Parameters sensitivity analysis.

Parameter	**Parameter Name**	**Rank**
Esco	Soil evaporation compensation factor	1
Cn2	Initial SCS CNII value	2
Sol_Awc	Available water capacity (mm H_2O/mm soil)	3
Sol_Z	Soil depth (mm)	4
Revapmn	Threshold water depth in the shallow aquifer for “revap” (mm)	5
Gwqmn	Threshold water depth in the shallow aquifer for flow (mm)	6
Canmx	Maximum canopy storage (mm)	7

Alpha_Bf	Baseflow alpha factor (days)	8
Blai	Maximum potential leaf area index	9
Gw_Revap	Groundwater “revap”[a] coefficient	10

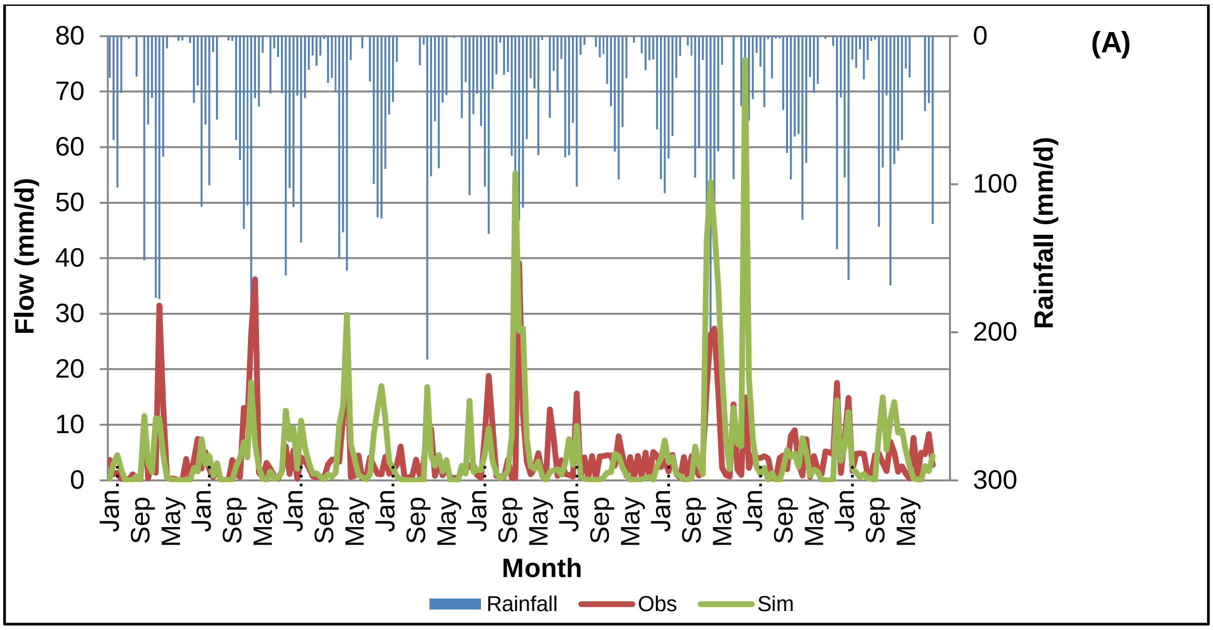
[a]Revap: In the SWAT model, this term means the movement of water into overlaying unsaturated layers as a function of water demand for evapotranspiration.

In the ArcSWAT interface, auto-calibration and uncertainty input window, location of sub-basin was specified where observed data will be compared against simulated output. Default values listed for the optimization settings were used. The default value of 2000 for MAXN, the maximum number of trials allowed before optimization is terminated, was used. However, the optimization process stopped after 6730 trails due to the fact that there was less than 1% change in parameters. Stream flow parameters that were calibrated were selected with their default lower and upper calibration bounds. Model parameters were calibrated against measured data at a single gauge which is situated at the outlet of the sub-basin.

4.2 Simulation results

Simulated stream flow data for each reach are stored in the output.rch file as an accumulated flow at an outlet for the reach. The gauging station measures the outflow of the study area. Measured stream flows from this station were compared with simulated stream flows at the same point. Simulation results are discussed in the subsequent paragraphs.

A graphical representation of the monthly simulation result against observed flows for the period 1993 to 2010 before calibration is shown in Fig. 4.4 (A). The non-calibrated model produced unsatisfactory results with high variation of minimum and maximum values in the flow pattern. The rate of change of the conditional mean simulated data with respect to observed data is equal to 0.848 and a very weak correlation coefficient which was equal to 0.29 (Fig. 4.3: B).



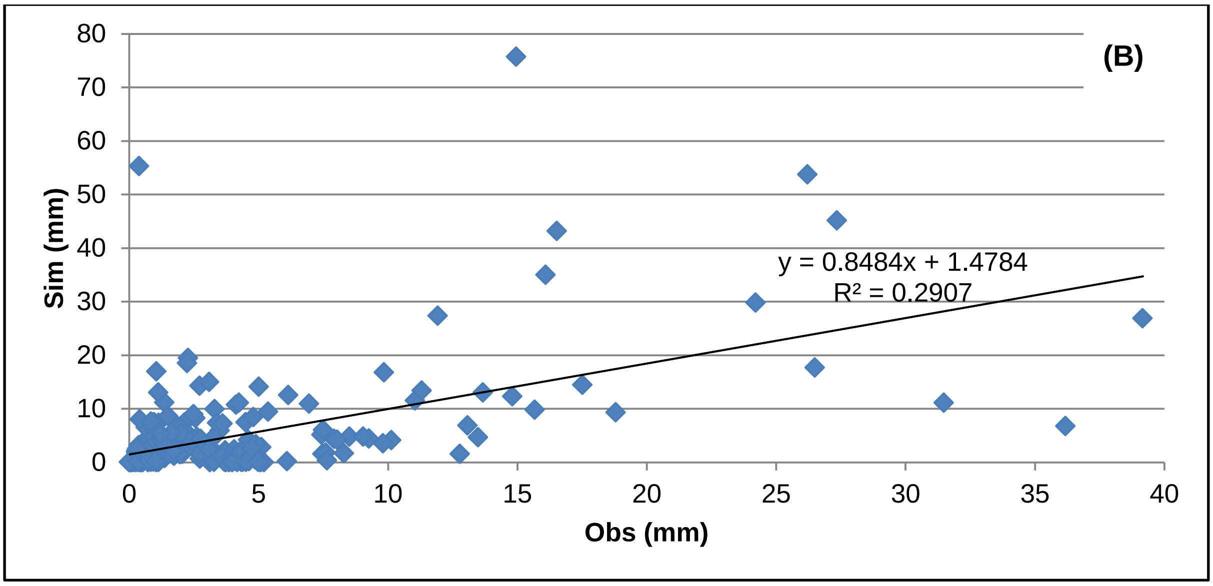
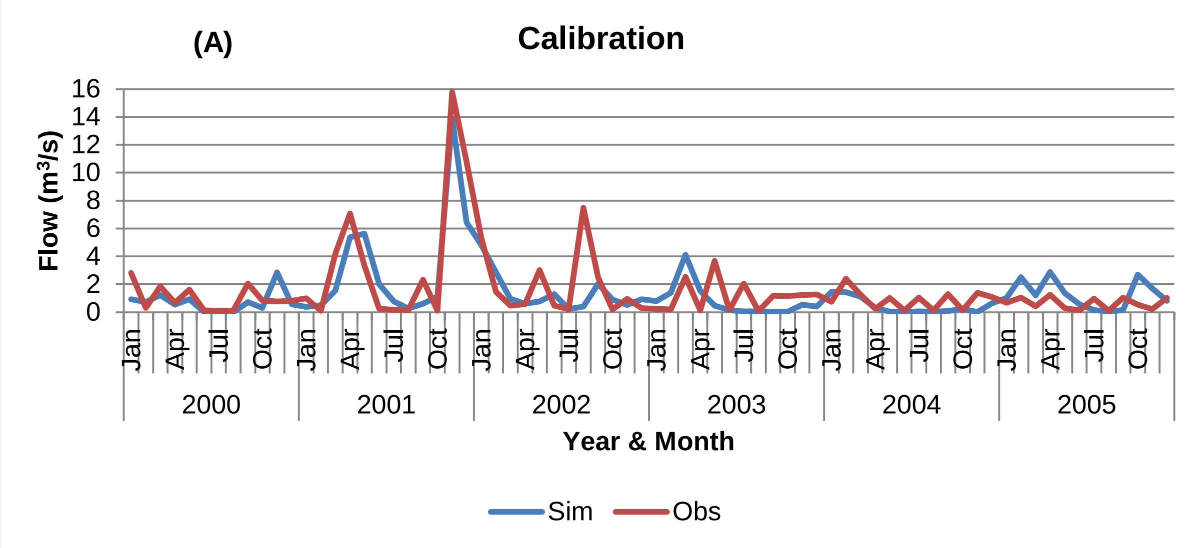


Fig. 4.5: (A) Monthly stream flow hydrograph before calibration (1993-2010) and (B) linear regression of observed and simulated data.

The monthly predicted flows for calibration and validation stage (Fig. 4.5: A & B) show that the model in general underestimates stream flow. This is also confirmed by the positive Pbias value during the calibration and validation period, which indicates underestimation bias while a negative value indicates overestimation bias by the model (Gupta et al., 1999; cited by Moriasi et al., 2007). In general calibrated and validated model results show a good comparison with the observed flow pattern.



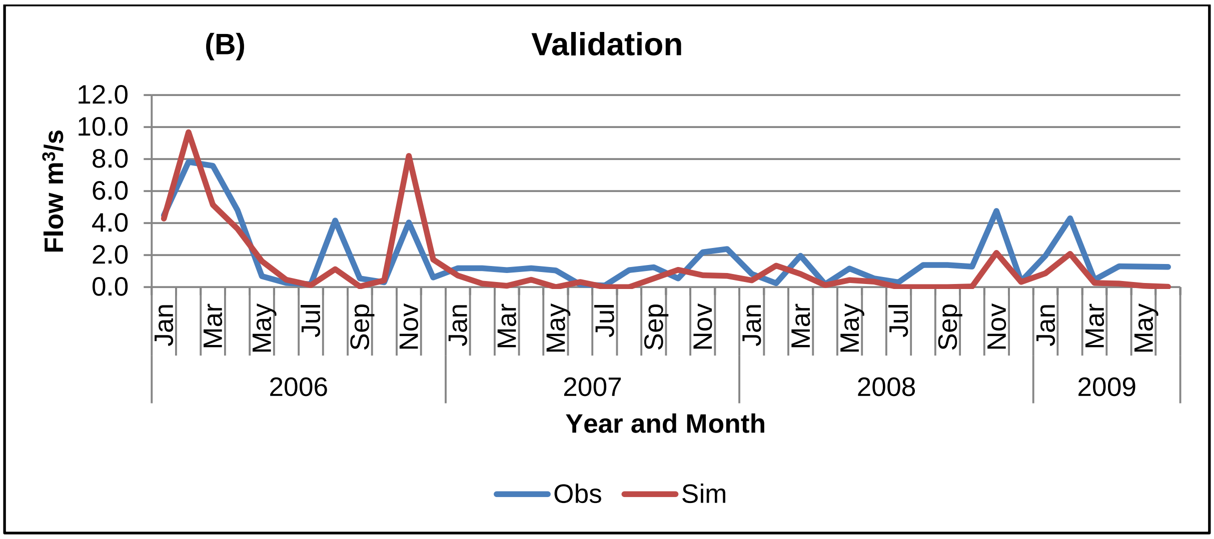
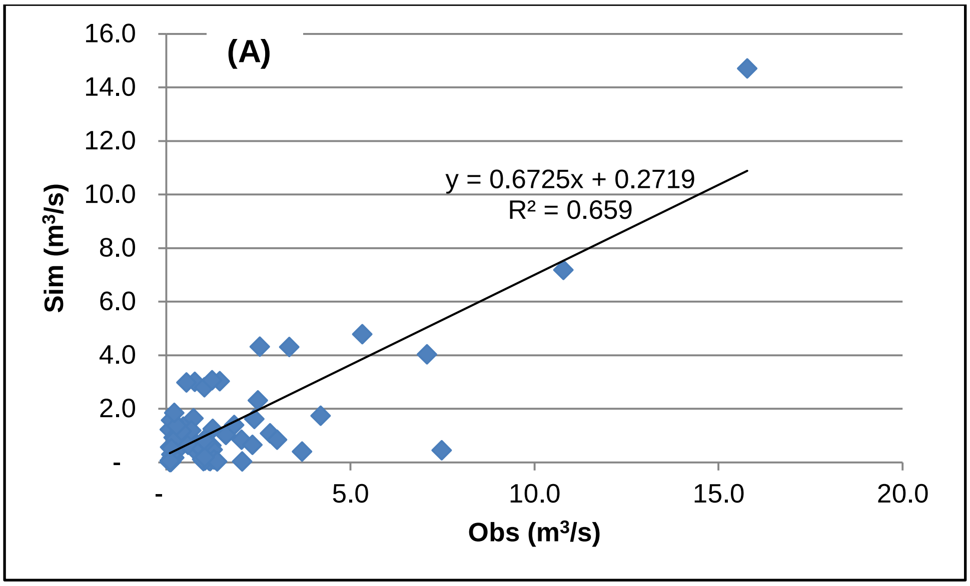


Fig. 4.6: Monthly observed and simulated stream flow for: (A) calibration stage and (B) validation stage.

In addition, through further graphical analysis of the calibrated and validated stream flow, the accuracy of the model can be demonstrated (Fig. 4.6: A & B). For the monthly time step stream flow simulation, the correlation between the observed and simulated stream flow during calibration and validation stages gave R^2 values of 0.659 and 0.658 respectively.



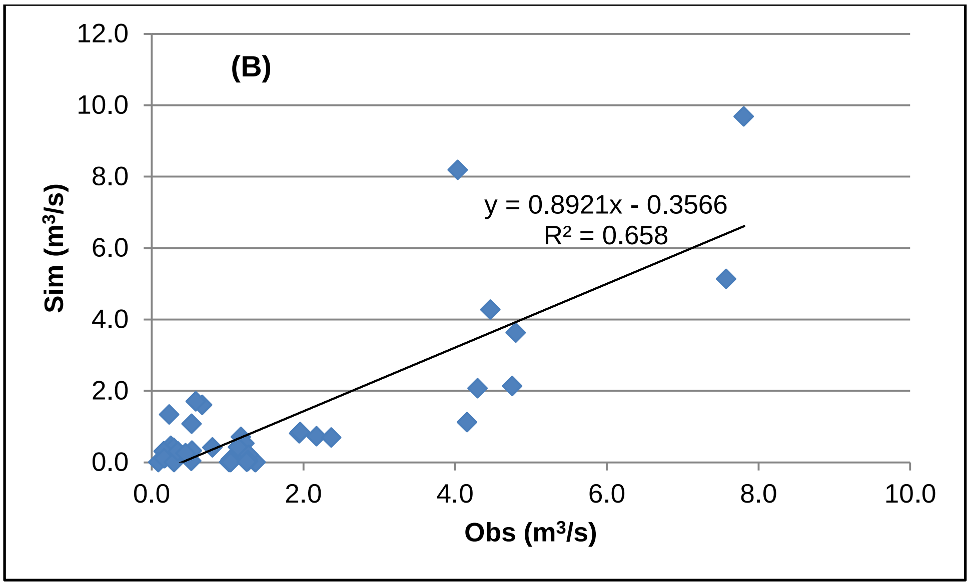


Fig. 4.6: Linear regression of observed and simulated data based on monthly time step for: (A) calibration stage, and (B) validation stage.

The yearly time step produced better correlation values with R^2 of 0.840 and 0.994 during the calibration and validation stages respectively (Fig. 4.7: A & B) compared to the monthly time step.

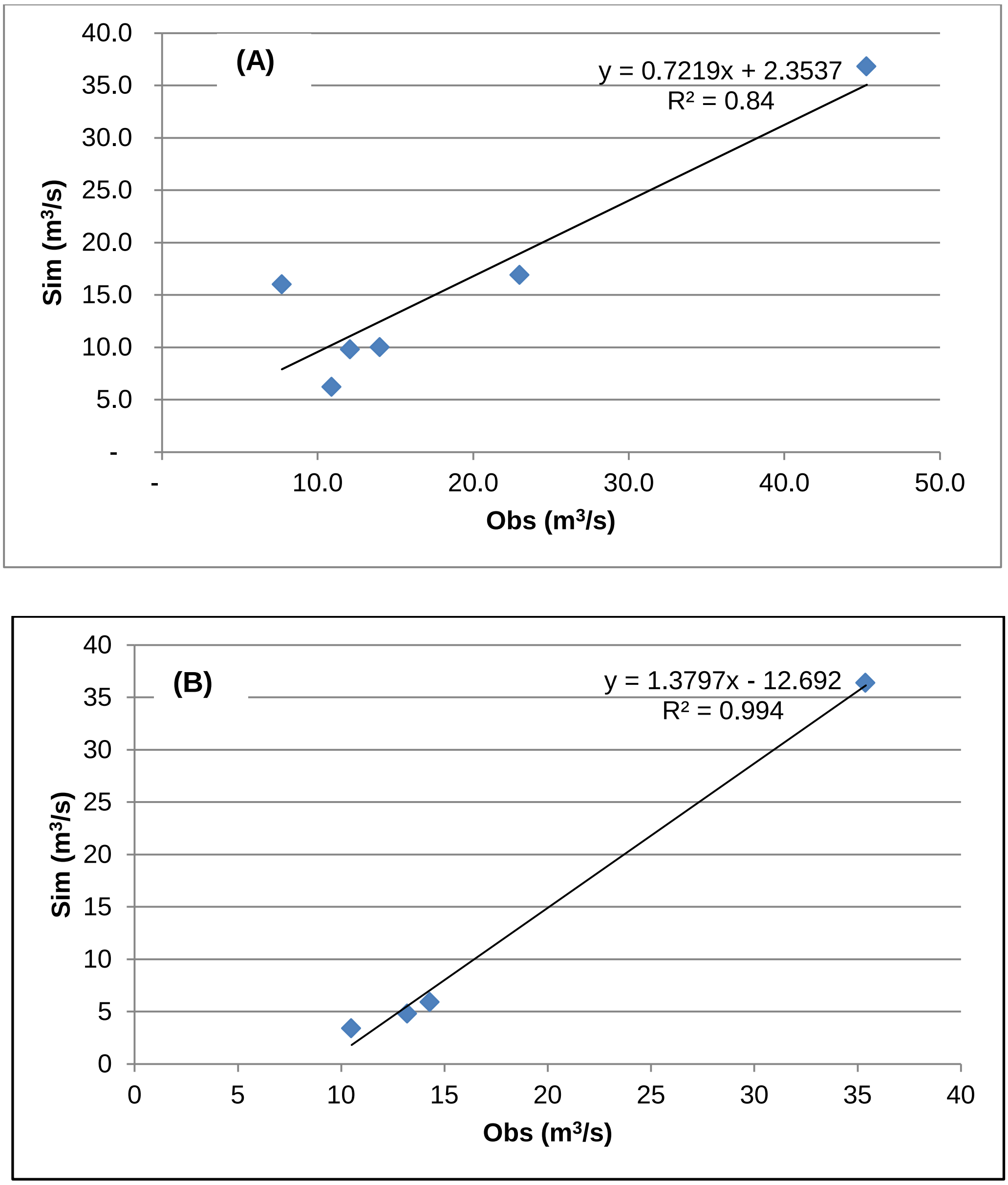


Fig. 4.8: Observed and simulated data for: (A) calibrated yearly flows, and (B) validated yearly flows.

A summary of the statistics for the non-calibrated, calibrated and validated model on monthly and yearly time step bases is presented in Table 4.6. When comparing the model's performance against the model evaluation criteria based on the guidelines (Moriasi et al., 2007) presented in Table 2.3 for the monthly time step, SWAT2005 simulated the stream flow trends well to very well. The RSR value of 0.4 gives the model performance rating as very good. Moreover, the NSE value of 0.65 gives the model performance rating as good while the Pbias value which is equal to positive 15 indicates the underestimation of the stream flow by the model. But the overall model performance showed a good rating during the calibration stage. The underestimation might be due to the possible influence of inaccurately generated data or inconsistency in data for precipitation and temperature.

Table 4.6: Summary of statistics for ArcSWAT simulated versus observed data.

Statistics	**Non-calibrated monthly**	**Calibrated monthly**	**Calibrated yearly**	**Validated monthly**	**Validated yearly**
NSE	-0.80	0.65	0.77	0.50	0.98
Pbias	-19	15	15	31	31
RSR	1.80	0.40	0.20	0.50	0.00
R^2	0.29	0.66	0.84	0.66	0.99
Slope	0.85	0.67	0.72	0.89	1.38
Y-Intercept	1.48	0.27	2.35	-0.36	-12.69

In a similar study conducted by Welderufael et al. (2013) at an adjacent catchment C52A, it was reported that Nash and Sutcliffe efficiency (NSE) has a value of 0.57 for the monthly time step calibration and 0.68 for R^2 for the daily time step calibration of the catchment stream flow. Jha (2011) reported R^2 of 0.86 and NSE of 0.85 for calibrated monthly flows, and for validation the following monthly flows statistics were reported: R^2 of 0.69 and NSE of 0.61. Srinivasan et al. (2010) reported R^2 of 0.75 and NSE of 0.74 for calibrated monthly flows, and for validation the following monthly flows statistics were reported: R^2 of 0.58 and NSE of 0.69. Bouraoui et al. (2005) reported R^2 of between 0.62 and 0.84 and NSE of between 0.41 and 0.84 for calibrated monthly flows. A coefficient of determination (R^2) value of 0.5 or greater for monthly time step calibrations is regarded as satisfactory model performance (Gassman et al. 2007) and for this study the R^2 is 0.66 and the NSE is 0.65.

During the validation stage the model performed well overall. The statistics at this stage for monthly time step are RSR value of 0.5 which gives the model performance rating of very good, NSE value of 0.5 gives satisfactory model performance rating, and a Pbias value of 31 shows that the model still underestimates stream flow. There was an improved performance by the model in representing the true system during calibration and validation stage from initial simulation, reaching acceptable performance level.

The statistics indices calculated agreed well with the guidelines recommended by Moriasi et al. (2007) for a monthly time step. The guidelines recommend that model simulation should be judged as "satisfactory" if NSE > 0.5 and RSR ≤ 0.7, and if Pbias ±25% for stream flow. Gassman et al. (2007) also suggested that NSE value should exceed 0.5 in order to consider the model's performance satisfactory for hydrologic evaluations performed on a monthly time step. In a related study, Wang and Melesse (2005) also reported that the SWAT model had a good performance in simulating the monthly, seasonal, and annual mean discharges.

The NSE coefficient indicates how well the plot of observed versus simulated data fits the 1:1 line. Values between 0 and 1 are generally accepted levels of performance (Moriasi et al., 2007). The RSR is calculated as the ratio of the RMSE and standard deviation, and optimal value is 0. Percent bias (Pbias) measures the average tendency of the simulated data to be larger or smaller than their observed data (Moriasi et al., 2007). An RSR value between 0 and 0.5 is considered very good performance by the model.

4.3 Model limitations and performance

The limitation of the SWAT model in predicting daily flow is probably due to the use of the curve number (CN2) method. A major limitation of the CN2 method is that rainfall intensity and duration are not considered, and only total rainfall volume is considered instead (Rallison & Miller, 1981; cited by Saleh & Du, 2004). The following are the reasons why the curve number method was chosen over infiltration equation (Arnold et al., 1998):

a) Less than one day rainfall is not always available and difficult to process.
b) Often sub-basins tend to be several square kilometres large when simulating large watersheds. It is easy to obtain weighted curve number and realistically simulate runoff.
c) Soils data is often available with insufficient spatial detail to justify using infiltration equation.
d) It relates runoff to soil type, land use, and management practices.

Calibration and validation results indicate that the SWAT model is an effective catchment management tool that can be applied with available data. The model demonstrated a satisfactory level of performance in modelling the hydrology of this catchment. Harmel et al. (2006) highlighted inaccuracies in stream flow data as a major factor affecting SWAT hydrological output while Saleh & Du (2004) found model efficiencies to be higher for monthly predictions than for daily predictions.

CHAPTER 5: CONCLUSION

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The global phenomena of climate change which is threatening the water resources at every corner of the world, including South Africa, requires rapid assessment of water yields for different sizes of catchment for better planning, management and sustainable use of the water resources. Therefore, seeking a suitable hydrological model that simulates the water yield of un-gauged catchments is also an important part that must go side by side with the water yield assessment.

The assessment of SWAT hydrological model and investigation into its ability to simulate reliably the different components of water balance in general and stream flow in particular using different efficiency criteria gave an insight into how one can successfully generate useful information in catchments where there is little data available. In order to do so, various efficiency criteria were implemented, namely, Nash and Sutcliffe (NSE), Percent bias (Pbias), RSR which is calculated as the ratio of the RMSE and standard deviation and correlation coefficient (R^2).

The results suggest that the SWAT hydrological model can be a useful tool which, once calibrated effectively, can produce meaningful catchment predictions to aid management decisions. The results obtained indicate that catchment output simulated by SWAT after calibration is comparatively consistent with recorded values. The research used the recommended model evaluation techniques and graphical and statistical analysis to evaluate the performance of the SWAT model in the study area. Particularly the hydrographs and the quantitative statistics NSE, RSR, and Pbias were used. The model performed well for the monthly time step simulation. During the calibration period the monthly stream flow gave the values for NSE, Pbias and R^2 as 0.65, 15, and 0.66 respectively. The SWAT model also performed well during the validation period for the monthly stream flow simulation giving NSE, Pbias and R^2 as 0.56, 31 and 0.66 respectively. Generally, the model performance in this study can be judged to have performed satisfactory after calibration of the model.

Zhang et al. (2008) reported that different optimization schemes can lead to substantially different objective function values, parameter solutions, and corresponding simulated hydrograph. This indicates that the selection of an optimization scheme can significantly impact on how well hydrologic models simulate actual stream flow.

The SWAT hydrological model has been shown to be a suitable model for applications in un-gauged catchments. This is especially important to note that in South Africa, there are limited number of gauging stations available. Moreover, the available measured stream flow data are often unreliable.

This study provided better understanding of SWAT model set-up, sensitive parameters that influence the model output, and hydrologic processes of the catchment. Calibration should be realistic and include only parameters that are relevant to hydrologic processes. The most sensitive parameters found in this hydrological simulation exercise were Curve Number (CN) which is dependent on land management practice and soil parameters. These parameters are found to influence hydrologic processes more than others. It is very important that calibrated model results provide reasonable reflection of actual hydrologic processes. Statistical evaluation criteria suggested by Moriasi et al. (2007) only provides the guidelines to which to evaluate model's performance. Moreover, it is also essential to look at other statistical indices that can be used to evaluate the model's performance. It is recommended that further study be conducted in order to evaluate uncertainties in the model that affect model performance and the sensitivity of the distributed hydrologic simulations to different calibration schemes under different catchment conditions.

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APPENDIX

APPENDIX

Appendix A: Output of Total Monthly Precipitation from pcpSTAT program.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total Yearly PCP
1950	30.6	53	131.1	107.2	61.8	7.6	36.2	43.3	5.3	12	45.5	77.7	611.3
1951	69.5	27.4	87.5	69.8	9.1	9.9	15.2	4.6	31.9	63.9	37.5	9.5	435.8
1952	48.8	80.1	60	15	6.1	3.3	51.8	12	32.2	27.4	70.9	82.2	489.8
1953	48.2	163	4.6	8.9	10.5	8.9	0	4.3	11	56.3	48.7	90	454.4
1954	27.3	88.4	189.5	16.8	37.9	4.4	0	0	0	8.8	46	52.4	471.5
1955	125.9	75	32.1	49.5	22.4	4.1	23.4	1.9	0	40.4	56.6	74.8	506.1
1956	80	162.4	116.1	42.2	28.2	0	4.5	0	15.6	87.6	45.5	121	703.1
1957	71	20.2	89.2	20	0	13.8	26.5	32.2	152.7	116.5	48.1	39.5	629.7
1958	94.8	38.3	65.6	48.5	70.7	1.2	0	0	64.2	41.7	124.2	155	704.2
1959	63.3	45.1	57	70.9	46.6	0	59.1	0	0	44.5	70.5	110	567
1960	32.8	45	144.4	83.2	14.9	12.2	16.6	22.9	17.4	74.4	57	104.8	625.6
1961	66	17.5	73.9	92.6	25.9	49	11.7	7.9	0	0	139.4	61.6	545.5
1962	27.7	113.9	53.3	48.9	14.4	0	0	0	0	11.9	101.3	63.6	435
1963	126.7	41.1	83.8	80.1	32.2	14.5	19.5	0	0	21.1	193.5	41.2	653.7
1964	10.6	52.9	80.1	53.3	8.1	28.4	0	0	2.6	58.9	70.4	77.6	442.9
1965	96.7	7.5	25.4	64.4	0	11.3	61.7	0	5.2	19.3	45.5	1.7	338.7
1966	183.7	85.4	24	27.5	0	20.7	0	0	0	28.6	56.6	65.6	492.1
1967	130.5	70	91.3	161.2	57.4	0	0	11.3	5.8	59.8	45.6	72	704.9
1968	19.6	10.8	114.8	93.5	73.5	0	14.2	4.1	19.5	41	36.5	58	485.5
1969	9	109.9	148.7	90.2	73	0	0	11.2	6.5	77.9	29.8	28.8	585
1970	83	17	8.7	23.7	14.4	17	35.1	13.1	72	21.2	45.1	49.6	399.9
1971	69.4	63.7	57.2	58.3	61	0	9.7	0	2.6	45.3	6.2	33.6	407
1972	144.8	168.6	133.5	19.7	24.6	15	0	1.9	0	33.4	21.8	0	563.3
1973	12.8	113.7	47.6	22.2	0	0	9.1	24.3	62.4	11	102.1	15.6	420.8
1974	214.4	66.9	75.4	20.1	25.8	0	0	19.8	0	26.9	152.4	50.8	652.5
1975	121.7	100	54.2	28.7	0	36.4	0	0	11	19.4	173	79.2	623.6
1976	230.9	149.1	131.5	50.8	21.3	16.2	0	0	13.6	114.4	27	26.4	781.2
1977	77.4	119.7	112.3	0	23	0	0	0	169.6	13.7	42.6	25.3	583.6
1978	60.3	48.2	170.1	104.4	0	3	0	7.1	50.6	3.3	9.1	74	530.1
1979	27.6	65.5	10.1	39.4	19.5	0	66.8	41.6	7.1	75.7	35.7	72.4	461.4
1980	54.9	56.9	58.1	14.8	2.9	0	0	6.4	85.7	0	85.8	19.4	384.9
1981	164.9	95.7	55.6	34.7	39.8	20.8	0	62.1	2.2	26.3	88	86.2	676.3
1982	13.2	54.2	56.7	122.2	0	16.9	34.5	0	37.2	86.6	61	55.4	537.9
1983	30.3	22.1	38.8	16.7	32.8	16	76.2	1.4	9.9	40.5	120.5	36.4	441.6
1984	51.2	29.5	63.2	15.2	61	0	0	24	0	59.9	43.8	15.5	363.3
1985	62.4	79.9	40.7	18	0	55.1	0	0	0	84.4	98.1	91.7	530.3
1986	59.5	42.1	82	16.4	0	14.9	0	21.8	38.3	108.5	99.2	29	511.7

1987	10.7	79.7	105.1	99.2	0	0	21.4	24.5	225.9	17.6	76.6	40.2	700.9
1988	51	222.4	55.6	70.3	14.1	16.6	4.5	5.9	61.7	100.7	54.3	100.7	757.8
1989	77.3	114.3	50.9	50.2	0	0	20.8	4.6	3.9	17.9	59	39.1	438
1990	59.6	73.8	125.9	83.8	2.9	22	8.4	10.8	0	7	1.6	27.6	423.4
1991	158.6	120.5	107.7	0	0	17.3	2.6	0	65.6	149	72.2	64.8	758.3
1992	27.9	17.7	20.4	17.7	0	0	2.6	15.9	0	34.8	87.4	20.2	244.6
1993	28.4	59.1	105.4	37.3	28.7	2.4	0	14.3	0	148.8	65.8	32.6	522.8
1994	153.2	107.1	73.5	11.2	0	0.9	0	0	0	1.3	43.5	34	424.7
1995	112.1	45.8	96.2	10.9	72	0.1	0	3.6	6.9	56.2	71.8	94.2	569.8
1996	85.5	170.3	33	63.5	11	0	52.5	5.9	18.8	59.7	130	92.5	722.7
1997	93.2	25.3	143.3	42.8	61.1	6.5	29.2	12.7	4.4	21.9	15.6	27.6	483.6
1998	140.8	83.1	153.5	10.5	0	0	9.9	0	39	83.2	102.6	111	733.6
1999	71.1	44.2	40.8	12.1	0	0	0	0	0	0	0	189.4	357.6

Appendix B: Observed flow data (m^3/s)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	2.8	0.3	1.8	0.7	1.6	0.1	0.1	0.1	2.1	0.9	0.8	0.8
2001	1.0	0.1	4.2	7.1	3.3	0.2	0.2	0.2	2.3	0.1	15.8	10.8
2002	5.3	1.5	0.5	0.6	3.0	0.5	0.2	7.5	2.5	0.2	1.0	0.3
2003	0.3	0.2	2.5	0.1	3.7	0.1	2.1	0.1	1.2	1.2	1.2	1.3
2004	0.7	2.4	1.3	0.3	1.0	0.1	1.1	0.1	1.3	0.1	1.4	1.1
2005	0.7	1.0	0.4	1.2	0.3	0.1	1.0	0.1	1.0	0.6	0.2	1.0
2006	4.5	7.8	7.6	4.8	0.7	0.3	0.2	4.2	0.5	0.3	4.0	0.6
2007	1.2	1.2	1.0	1.2	1.0	0.2	0.1	1.0	1.2	0.5	2.2	2.4
2008	0.8	0.2	1.9	0.2	1.1	0.5	0.3	1.4	1.4	1.3	4.8	0.3
2009	2.0	4.3	0.5	1.3	1.3	-	-	-	1.3	-	-	-

Appendix C: SWAT Output of Land Use, Soil and Slope Classification for C52B Catchment.

Catchment Characteristics:

Catchment Characteristics	
Number of Hydrologic Response Units	65
Number of Sub-basins	24
Catchment Area (Ha)	69946.00

Land use information:

Land Use	**Area (Ha)**	**%Catchment Area**
Pasture - PAST	62298.9013	89.07
Residential - URBN	5320.3993	7.61
Range-Brush - RNGB	829.2400	1.19
Wetlands-Non-Forested - WETN	103.0864	0.15
Agricultural Land-Row Crops - AGRR	1394.3730	1.98
Total	69946.0000	100.00

Soil:

Soil Type	**Area (Ha)**	**%Catchment Area**
Dc 17	69946.0000	100.00

Slope:

Slope (%)	Area (Ha)	%Catchment Area
0-3	48383.6183	69.17
3-5	12181.1552	17.42
5-10	9381.2264	13.41