MODELLING HYDROLOGICAL PROCESSES IN THE CHANIA RIVER SYSTEM

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JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY.

2018

Modelling Hydrological Processes in the Chania River System

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A thesis submitted in partial fulfillment for the degree of Master of Science Civil Engineering of Jomo Kenyatta University of Agriculture and Technology.

2018

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

Signature ………………….. Date…………………………………..

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This thesis has been submitted for examination with our approval as University Supervisors

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JKUAT, Kenya

DEDICATION

This thesis is dedicated to my loving husband, my daughter and my siblings. Your support and prayers have made me to come this far in my studies. God bless you all abundantly.

ACKNOWLEDGEMENT

First and foremost I wish to express my gratitude to God. He provided the gift of life, strength and grace to go through my studies. I wish to convey my most sincere gratitude to my supervisors Dr. Eng. J. Kiptala and Dr. J. Mwangi. Your guidance, support and constructive criticism were highly appreciated. Thank you for finding time in your busy schedules to go through my work and offering tips on how to improve the thesis.

I would like to thank the staff of Jomo Kenyatta University of Agriculture and Technology Civil Engineering department for their assistance during my studies. I would also to thank my classmates for their constant encouragement and the intellectual discussions we had. My special thanks go to John and Lorraine. I would also like to acknowledge the Kenya Meteorological Department for providing weather data and Water Resources Management Authority for providing stream flow data.

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LIST OF ABBREVIATIONS AND ACRONYMS

CN2	Curve Number
DEM	Digital Elevation Model
ET	Evapotranspiration
FDC	Flow Duration Curve
GIS	Geographic Information System
HRU	Hydrologic Response Unit
ISRIC	International Soil Reference and Information Centre
LATQ	Lateral Flow
LH-OAT	Latin Hypercube One factor At a Time analysis
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent Bias
R^2	Coefficient of determination
SWAT	Soil Water Assessment Tool
TEDPAS	Temporal Dynamics of Parameter Sensitivity
USDA	United States Department of Agriculture
WRUA	Water Resources Users Association
WRMA	Water Resources Management Authority
WYLD	Water Yield
KNBS	Kenya National Bureau of Statistics

ABSTRACT

Kenya is classified as a chronically water-scarce country in terms of availability of water resources. This study was conducted in the Chania catchment located within the upper Tana catchment. Common water resources related problems experienced here are mainly related to water scarcity and deforestation. Hydrology plays an important role in providing information which will assist in overcoming the water shortage related problems in catchments. The main objective of this study was to model hydrological processes in the Chania catchment. The SWAT model was calibrated and validated using stream flow data for the years 2001-2004 and 2005-2008 respectively. Hydrological processes governing the temporal variability of stream flow were investigated using the Fourier Amplitude Sensitivity Test (FAST). The spatio-temporal variability of water balance components was determined from the model upon successful calibration. Effects of land use changes were investigated by using various land use scenarios. Results of calibration gave NSE of 0.67, R^2 of 0.69 and Percent Bias (PBIAS) of 8.87 signifying a good performance. For validation NSE was 0.53, R^2 was 0.59 and PBIAS was 12.24, signifying a satisfactory results. Results from FAST show that runoff processes were active mostly during precipitation events. Soil and ground water processes were most dominant in this catchment with a distinct presence during low flow seasons. The water balance components varied in both time and space. High quantities of ground water and water yield were noted in the north western side of the catchment. The average annual precipitation varied from 2376.57mm to 1499mm. Surface runoff ranged from 344.03 to 129.22mm with the highest value being recorded during the highest precipitation events. Ground water values range from 503.66mm to 765mm. Lateral flow values ranged from 291.40mm to 510.5mm while ET ranged from 670 mm to 850 mm. Investigations of effects of land use change on water balance show that decreasing forest led to a reduction in ground water, water yield and lateral flow. Urbanization reduced ground water, lateral flow and ET but lead to an increase in water yield and surface runoff. In conclusion, the SWAT model can be successfully used in

Chania catchment to model hydrological processes. The variability of water balance components depended on the amount of precipitation, land cover and soil type. Since deforestation exacerbated water scarcity, it is therefore recommended that deforestation in the Chania catchment should be controlled while afforestation should be undertaken to restore the catchment

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Water is a finite and vital resource. It is essential for agricultural use, industry and human existence. For development to occur, water must be adequate both in quality and quantity. Globally, water is becoming scarce and its quality is also deteriorating (Sameer, 2008). The demand for water has increased significantly due to population growth, expansion of industries, demand for food in arid and semiarid areas and improved living standards. Due to these trends, water resources management is critical to ensure availability of water and to protect it against deterioration in quality (Sameer, 2008).Water is also viewed as a resource to generate renewable energy by constructing dams for generating hydropower to meet energy demands essential for economic growth (Tessema, 2011).

Kenya is classified as a chronically water-scarce country in terms of quantity (Mumma et al., 2011). It has one of the world's lowest water replenishment rates per capita .There is limited access to safe water and sanitation services especially due to population growth. In many parts of the country, water scarcity has become a hindrance to development activities. The water crisis in the country can be attributed to droughts, degradation of forests, and inadequate management of water supply and occurrence of floods (Samantha, 2011). Degradation of water resources has been estimated to cause losses of at least Ksh 3.3 billion annually to the country (Mogaka et al., 2006). A research paper from the World Bank by Grey and Sadoff (2002) suggests that continued mismanagement of water resources, degradation due to deforestation, pollution, and the absence of preparation for climate change are causing increase in poverty and undermining economic growth, not only in Kenya but across the African continent.

Chania catchment is located in Kenya within the upper Tana catchment. The catchment is important for Nairobi's water supply. The available water resource within Chania catchment currently does not adequately meet the demand due to increasing population with diminishing water resource quantity and quality especially during dry periods. Other water resources issues in this catchment include deforestation, urbanization and industrialization (WRMA, 2012). Generally, deforestation affects the hydrology of catchments by increasing runoff and altering the evapotranspiration rates (Zhang et al. 2001).

Hydrological studies are vital in curbing water shortage related problems in catchments through reliable evaluation of water quantities which will result in management of water resources in a sustainable way. Assessment of water resources is crucial for integrated water resources management. The outcome of the assessment is useful in decision making and formulation of policies. Decisions made without basis can cause large losses in investments and have detrimental effects on the environment.

Therefore, this research aimed at gaining an understanding of the hydrological processes in Chania catchment and quantification of water balance components. This was achieved through modeling of hydrological processes in the catchment. Due to problems of deforestation and urbanization in the catchment, effects of land use changes on the water balance of the catchment were also investigated.

1.2 Problem Statement

Most of the problems experienced in Chania Catchment are due to anthropogenic disturbance. There is over exploitation of the available water resources as demand mostly exceeds supply (WRMA, 2012). Furthermore, domestic, irrigation and industrial water demands in Chania catchment are increasing rapidly due to fast industrialization and urbanization in the region.

The region has also undergone numerous changes in land cover and land use due to population growth and urbanization. There is increased encroachment into riparian land and deforestation in the water towers is a major problem (Kigira, 2007). These changes have profound effect on the surface hydrology. Paved surfaces and bare ground do not encourage infiltration. As a result, base flow contribution to the river is reduced resulting in low flows during dry seasons. This leads to water scarcity especially in dry seasons. These factors contribute greatly to the complexity of management of the catchment. Chania water resource is classified as alarm due to the water resource problems it faces which deteriorates the available water resources in terms of quality and quantity (WRMA, 2012). Chania Water Resources Users Association (WRUA) has low data essential for sustainable water resource management. This is partially contributed by the poorly gauged nature of the catchment.

1.3 Objecives

1.3.1 General Objective

To model hydrological processes in the Chania River system.

1.3.2 Specific Objectives

1. To develop SWAT model for use in Chania River system.
2. To determine the hydrological processes which govern the temporal variability of stream flow in the catchment.
3. To determine the spatio-temporal variation of water balance components within the Chania catchment.
4. To assess impacts of land cover changes on the water balance and hydrology of the catchment.

1.4 Research Questions

1. What are the optimum parameter values for simulation of hydrological processes in Chania catchment using SWAT model?
2. What are the hydrological processes that govern occurrence and temporal variability of stream flow?
3. What are the temporal and spatial values of water balance components of the Chania catchment?
4. What are the potential impacts of land use changes on the water balance and the hydrology of the catchment?

1.5 Justification

Chania catchment has forests such as the Aberdares and Kieni forest which are important water towers in the area. Simulating hydrological processes of this region is useful in appreciating the dominant hydrological processes which control the water balance. Modelling hydrological processes provides a comprehensive analysis of mechanisms which are associated with the dynamic processes which influence water resources. This in turn helps in estimating the water balance and determining the impacts of land use in the hydrology of the catchment. The results of this study will offer guidance in decision making for catchment management and in proper land use practices.

1.6 Scope

The study was limited to the geographical area encompassed by the Chania river catchment. Hydrological processes that were investigated include surface runoff, groundwater, lateral flow and evapotranspiration.

1.6 Study Area

1.6.1 General description of the catchment

The Chania catchment is located within the Upper Tana catchment. It covers an approximate area of 500 km^2. It is found between latitudes 0.753S and 1.04S and longitudes 36.58 E and 37.07 E as indicated in Figure 1.1. Chania catchment covers the following Administrative Districts: Gatanga, Gatundu North, Thika and Nyandarua South. The catchment straddles across Mang'u, Chania, Kariara, Gatanga, Thamuru, South Kinangop and Thika Municipality Divisions covering 19 Locations. The human population in this area has increased over time. In 1979, the population density of Murang'a, Kiambu and Nyandarua was 267, 280 and 66 persons per square kilometre respectively (KNBS, 1990). In the year 2009, the population density of Muranga South, Murang'a North, Nyandarua South and Kiambu West was 370, 422, 194 and 466 persons per square kilometre respectively (KNBS, 2010).

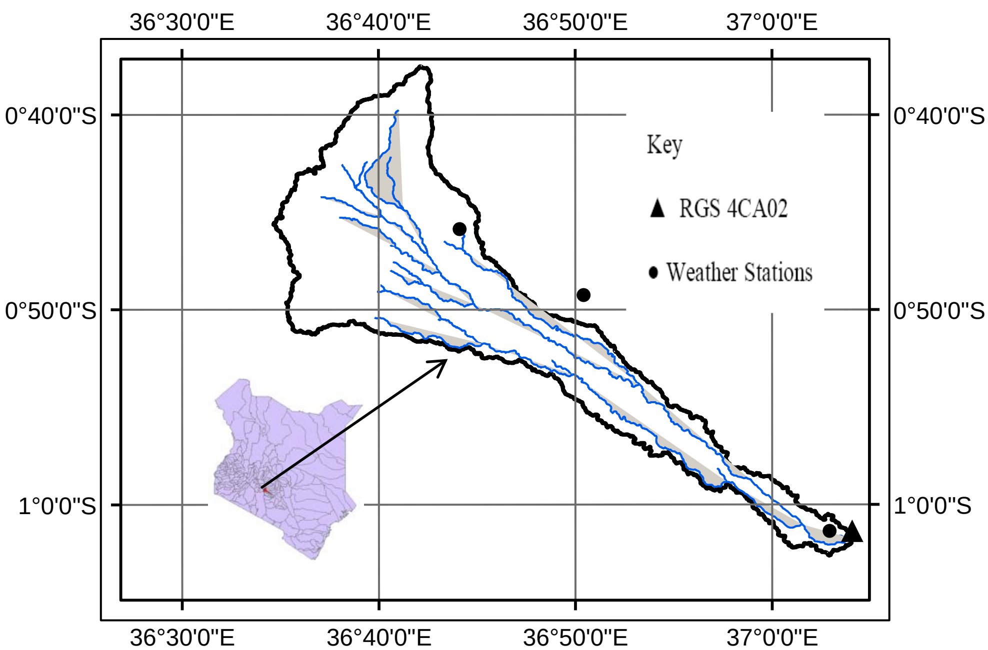

Figure1.1 Map of Chania River System

1.6.2 Hydrology and Climate

Chania catchment is drained by River Chania which enters the catchment at Ragia Location in Nyandarua South District flowing downstream to the confluence of Thika and Chania rivers behind Blue Post Hotel. Chania River is served by; Kariminu, Nyakibai and Kimakia, as the main tributaries all forming a dendrite drainage pattern. Besides the tributaries the catchment has several streams, springs, wetlands, boreholes and Dams.

The catchment mainly experiences two rain seasons, long rains from March to May and short rains from October to December. The hydrology of the catchment is greatly influenced by climate variability, Topography, land use among other factors which has impacted the resource quality and quantity. Mean annual minimum and maximum temperatures experienced in the catchment are 10°C and 22°C, respectively (Jaeztold et al.,2006).

1.6.3 Land use

There are diverse land uses within the catchment. Parts of the catchment are used for Agricultural purposes mainly tea, coffee, horticulture, dairy and subsistence farming (Hunink et al., 2012). Figure 1.2 shows tea plantations in the catchment. Some parts of the catchment contain settlements which include mainly rural and upcoming towns. A portion of the catchment is under forest cover (Kieni and Kimakia of Aberdare). The other category of land use consists of social, industrial, transport and commercial establishments (WRMA, 2012). There are also road networks of all classes (Tarmac, All-weather roads.. e.t.c)

Figure 1.2: Tea plantations in Chania Watershed (Source: Hunink and Droogers, 2015)

1.6.4 Soils

Soils in Chania River catchment vary with elevation and parent material. Deep in the forest the soils are well drained, very deep, dark reddish brown, very friable and smeary, silt clay loam, with humic top soil of mollic andosols combined with well drained, very deep, dark reddish brown to very dark greyish brown, friable and slightly smeary clay, with a humic topsoil of andocurvic phaeozems. Soils in the eastern side of the Aberdares forest are well drained, deep to very deep, reddish brown, friable clay, with acidic humic top soils (ando-humic acrisols) (Kigira, 2007; Hunink & Droogers, 2011).

1.6.5 Topography

The land slopes generally in the eastern direction. The highest altitudes range from 2500-2800 m.a.s.l. At the catchment outlet altitude is around 1500 m.a.s.l.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The literature review covers hydrological processes and modeling, Temporal Dynamics of Parameter Sensitivity and impacts of change in land use on the hydrology of a catchment.

2.2 Hydrologic Processes

Hydrological processes are processes pertaining to the hydrologic cycle. Water on earth is continuously on the move from one point to another in different forms and can be adequately explained through the hydrologic cycle (Subramanya, 2008). The various processes taking place in the hydrologic cycle include evaporation, transpiration, interception, infiltration, surface runoff and percolation. These processes influence how water is distributed in both space and time (Chow et al., 1988). Precipitation can fall on the earth in various forms such as rainfall, hail or snow. A portion of the precipitation will be intercepted by leaves of vegetation while others will fall on water bodies, soil surfaces and paved areas. Water which fell on vegetation, soil and water bodies may be lost through evaporation. Vegetation also loose water through stomata by transpiration. Water which fell on soil surfaces might flow as overland flow or infiltrate into the soil. Infiltrated water recharges aquifers and contributes to river base flows. Overland flow, subsurface flow and base flow contribute directly to stream flow in a river.

2.2.1 Factors affecting hydrological processes

Hydrological processes occurring in the hydrological cycle are interdependent. This means that when one process is affected the others are also affected. Runoff processes are affected by precipitation characteristics, drainage basin characteristics, geological characteristics, meteorological characteristics, geographical characteristics and land use. Rainfall of high intensity, high frequency and longer duration results in higher generation of runoff. Soils with high permeability promote infiltration thus reducing runoff and increasing ground water recharge (Sharma & Sharma, 2008). High temperature, strong wind and low humidity lead to high evaporation losses and reduced runoff. Land cover containing vegetation with high Evapotranspiration rates lead to more losses through evaporation.

2.3 Hydrological Modelling

Hydrological modeling has become a very vital part in decision making processes for water engineers and managers. Hydrological models represent hydrological processes occurring in the hydrological cycle in a more simplified manner. These models can be used to test various hypotheses or to make predictions. They can also be used in determining the availability and sustainability of water resources. Hydrological models are useful in understanding hydrological responses of a catchment and how certain changes in the catchment can influence those responses. Effect of land use changes on a catchment can be investigated using hydrological models (Sameer, 2008).

2.4 Hydrological Models

According to Dingman (2002), ―a model is a demonstration of a portion of the natural or man-made world, which can generally be classified as analog, physical, or mathematical (Figure 2.1). A physical model is a simpler scaled-down version of a real world (Brooks et al., 1991). In analog models, natural processes are represented in simpler and more understandable methods which can be analyzed. The mathematical models incorporate equations and numeric logical actions to get numeric outputs as a result of numeric inputs (Dingman, 2002). Rapid advances in computer technology have resulted in the phasing out of analog and physical models. Mathematical models are widely used in their stead. Mathematical models are further classified in different categories as shown in Figure 2.1. These categories are based on the characteristics of the model, spatial specification and temporal description in the model (Daniel et al., 2011; Lastoria, 2008). Empirical models are derived from experiments while theoretical models are based on theoretical principles and physical laws (Brooks et al., 1991). In deterministic models, each parameter is determined by the governing equations, while in a stochastic models, the parameters or input variables are partially or completely described by use of probability equations. Contrary to lumped models, distributed models take into consideration the spatial variability of input parameters (Warren & Gary, 2003).

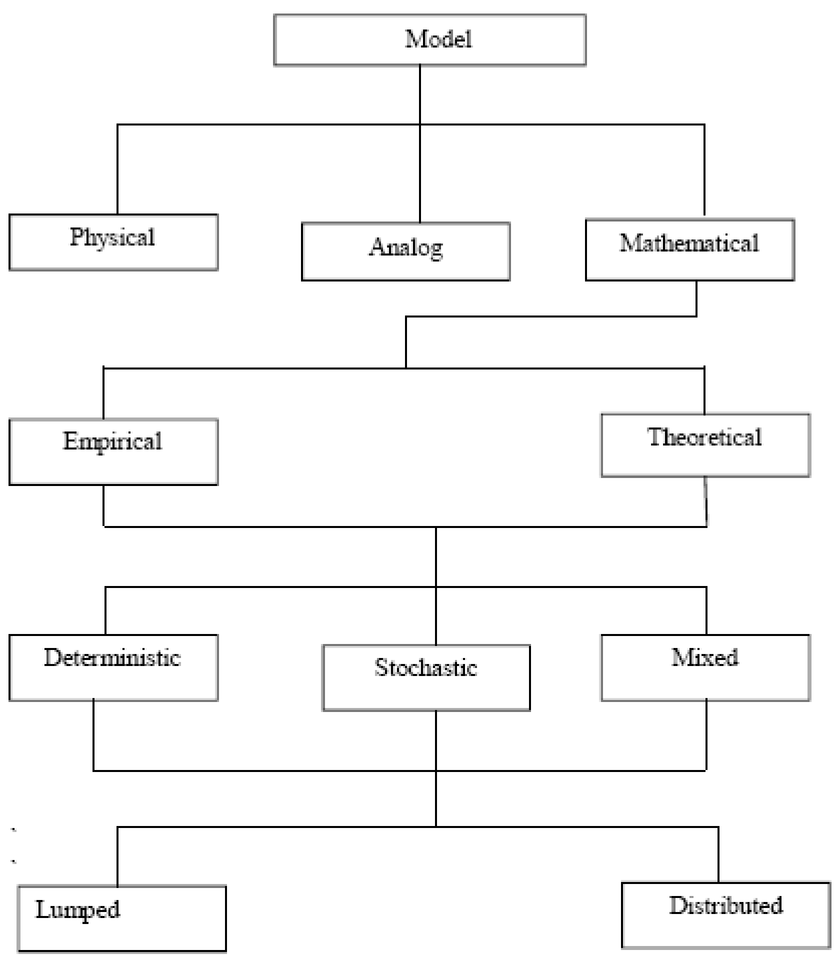

Figure 2.1 Classes of Hydrological Models (source: Ogothoo, 2006)

Hydrologic models are used to predict hydrologic responses of a catchment and to enable a researcher to study the role and interaction of different inputs. This helps the researcher to gain a better understanding of hydrologic processes in the catchment of interest (Brooks et al., 1991). The aim of hydrologic modeling is to determine the movement and distribution of water over land surface, below land surface, and in-stream flow. Hydrologic modeling also determines the quantity of water which in stored in natural water bodies and in the soil. Changes in quantities over a given time period can also be determined.

2.4.1 SWAT Model

SWAT model is a basin scale semi-distributed model, with more than 1230 publications published after applying the model in the various researches (Galvan et al, 2014). The Soil and Water Assessment Tool (SWAT) was developed by Dr. Jeff Arnold for the USDA Agricultural Research Service. SWAT was chosen for this study for its focus on modeling the hydrology of a catchment, while specifically accounting for the interactions between regional soil, land use and slope characteristics (Arnold et al. 1998). The input data required by SWAT includes weather data and spatial data such as soil, Digital Elevation Model and land use maps.

SWAT first divides the basin into sub-basins based on the topography of the area, followed by further discretization using soil type and land use. Areas with the similar land use and soil type form a Hydrologic Response Unit (HRU); a simple computational unit which is assumed to be homogeneous in hydrologic response to land cover change.

Mostly water enters in the SWAT watershed system in form of precipitation such as rainfall or snow. Parameters influencing flows and water quality are directed in the model on the basis of HRU to each sub basin and subsequently to the watershed outlet. In the present study SWAT model integrated with Arc GIS techniques was used to simulate the hydrology of the Chania catchment.

SWAT performs a day to day mass balance and contains eight modeling components – hydrology, weather, plant growth, nutrients, soil temperature, land management and pesticides. The hydrologic component of SWAT partitions precipitation into four control volumes: (1) the surface, (2) the soil profile or root zone, (3) the shallow aquifer, and (4) the deep aquifer. SWAT hydrologic simulations are based on the water balance Eq. 2.1:

$$SWt=SWo+\sum(Rday-Qsurf-Ea-wseep-Qgw) \qquad \text{Eq. 2.1}$$

SW is the soil water content (mm water) at the end of time step t (days), SW_0 is the initial soil water content on day i(mm water), R_{day} is the amount of precipitation on day i(mm water), Q_{surf} is the amount of surface runoff on day i(mm water), E_a is the amount of evapotranspiration on day i(mm water), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm water), and Q_{gw} is the amount of base flow from the shallow aquifer on day i(mm water).

A water balance is computed for each HRU at every time step. A summary of the resulting water balance at the end of each (daily) time step can be viewed in the HRU output file. SWAT simulation divides precipitation that falls on the soil surface into surface runoff (Q_{surf}) and infiltration with other options for water movement in SWAT, including recharge to the shallow aquifer and subsequent groundwater discharge. Surface runoff is calculated using the empirically derived SCS Curve Number (CN) method (USDA-SCS, 1972), with the amount of infiltration determined as the difference between the amount of precipitation and the amount of surface runoff. SWAT provides an option for modeling infiltration explicitly using the Green-Ampt method .The USDA Soil Conservation Service (formerly SCS; now NRCS) CN method is an infiltration loss model which aggregates (lumps) spatial and temporal variations into a calculation of "direct runoff" for a given storm depth and drainage area. Developed in 1954, the SCS CN method is used for estimating runoff volumes. The equation for determining direct runoff fusing the CN method is given as Eq. 2.2:

$$Qsurf=\frac{(R_{day}-0.2S)^2}{R_{day}-I_a+S} \quad \text{Eq. 2.2}$$

Where Q_{surf} is accumulated runoff, R_{day} is rainfall depth for the day in mm, I_a is Initial abstractions which includes surface storage, interception, infiltration prior to runoff in mm, S is retention parameter in mm.

The retention parameter is dependent on changes in land use, soil, management and slope and temporarily due to changes in water content. The retention parameter is defined using Eq. 2.3 as:

$$S=25.4\left(\frac{1000}{CN}-10\right) \quad \text{Eq. 2.3}$$

Where *CN* is the curve number ($0 \leq CN \leq 100$).

The initial abstraction, I_a, is commonly approximated as 0.2S and Eq. 2.4 becomes

$$Q_{surf}=\frac{(R_{day}-0.2S)^2}{R_{day}+0.8S} \quad \text{Eq. 2.4}$$

There are three different methods which have been incorporated in the SWAT model to calculate Potential Evapotranspiration: the Penman Monteith method (Monteith, 1965; Allen, 1986; Allen et al 1989), the Priestley-Taylor method (Priestley & Taylor, 1972) and the Hargreaves method (Hargreaves et al 1985). These three methods have different input data requirements. The Penman Monteith method requires relative humidity, solar radiation, wind and air temperature. The Priestley- Taylor requires air temperature, solar radiation and relative humidity. The Hargreaves method requires air temperature only making it the preferred method of calculation of PET for this research. Furthermore, several studies have indicated that Hargreaves method performs better than the Penman-Monteith method (Setegn et al., 2008 ;Wang et al., 2006). Uncalibrated outputs produced by using the Hargreaves method demonstrated a better fit between observed and simulated flows.

2.5 Sensitivity Analysis

2.5.1 Sensitivity analysis for Calibration Purposes

Before calibration and validation of a model, sensitivity analysis should be done to determine the most sensitive parameters required for calibration (Ma et al., 2000). There are two general methods of performing sensitivity analyses; local sensitivity analysis methods and global sensitivity analysis methods. The local sensitivity analysis changes only one parameter at a time (OAT) while fixing the values of the other parameters. It does not take into account how the parameters interact. This is a major disadvantage of this method given that the sensitivity of a parameter in dependent on the value of other related parameters. Furthermore, the results from a single-parameter combination do not represent the whole parameter space (Sudheer et al., 2011; Reusser 2011). Global sensitivity analysis on the other hand changes all parameters at the same time. This make it to be more computationally intensive therefore requiring a large number of simulations to perform the sensitivity analysis. Van Griensven and Meixner, (2006) combined the Latin hypercube, a global sensitivity method, with one-at-a-time method to come up with an efficient screening method that considers the whole parameter range. This combination (LH-OAT) was preferred in this study to perform sensitivity analysis for calibration purposes. It is a more robust method which ensures that the full range of all parameters has been sampled while incorporating the precision of an OAT design.

2.5.2 Application of TEDPAS in identifying hydrological Processes

Hydrological models are very useful tools in describing the existing hydrological conditions and to predict the future situations in a catchment. The output of the hydrological model can be evaluated for the whole time series or for smaller portions of the hydrological period. Due to the variation of dominant hydrological processes over time for example between dry and wet periods, the dominant components will change temporally. Assuming that dominant hydrological processes are described sufficiently in the corresponding model components and their relevant model input parameters, the dominant hydrological processes can be effectively determined by use of temporal dynamics of parameter sensitivity (TEDPAS) (Sieber , Uhlenbrook, 2005; Reusser et al., 2011).

Before performing sensitivity analysis on model parameters, the goal of the analysis should be clear as this will influence the choice of method to be used. According to Saltelli, there are different goals of sensitivity analysis (Saltelli et al., 2006). Factor prioritizing is useful in identifying dominant model components along a time series (Reusser, 2011). The factor fixing option on the other hand focuses on parameters that have the least effect on the output of interest and can be fixed to any value without upsetting the calibration process. Factor mapping option is used for calibration studies such as the generalized likelihood uncertainty estimation method (Beven, Binely, 1992).

The result of Sensitivity analysis for calibration purposes is a ranking of the input model parameter according to their sensitivity for the selected output variable. Such sensitivity does not consider the temporal dynamics of parameter sensitivity (Reusser, 2011). An analysis of TEDPAS has a different goal from the common use of sensitivity analysis for calibration purposes. In contrast to results of sensitivity analysis for calibration which ranks parameters, temporally resolved sensitivity analyses show periods in a time step where model parameters are sensitive. The output of TEDPAS illustrates the variations of the sensitivities with time. The generated time series of parameter sensitivity can be used in identifying dominant hydrological processes at a temporal scale (Guse et al., 2013; Reusser, Zehe, 2011).TEDPAS determines the parameter sensitivity of the model output for every time step. Identification of dominant model parameter is associated with the factor prioritization setting. This is best solved through methods that estimate the first-order partial variance as a measure of sensitivity (Saltelli et al., 2006). Partial variance-based methods modify the parameters at the same time. This method investigates how the variance of the model output depends on these parameter modifications in Eq. 2.5, from Reusser , 2011. The first-order partial variance is defined as the variance caused by changes in a certain parameter divided by the total variance V over all model runs (Reusser, 2011).

$$V=\sum iVi +\sum i<j\ V\ ij+\cdots+V1,2,3\ldots,n \qquad \text{Eq. 2.5}$$

Where V is the total variance, V_i the variance of parameter θi (first-order variance) and V_{ij} the covariance of θi (second-order variance) and θj higher-order terms. Any global sensitivity analysis method suited for factor prioritization can be applied for TEDPAS.
A number of methods such as Sobol's method and Fourier Amplitude Sensitivity Test (FAST) have been developed to work in the presence of non-linearity and to determine the results of parameter interactions (Saltelli et al 2006, Cibin et al 2010; Nossent et al 2011).
A number of researchers have applied TEDPAS in hydrological modelling. Pfannerstill et al., (2015) applied TEDPAS, using FAST, to a hydrological model to simulate hydrological processes in Kielstau catchment in Germany. The authors used actual observed processes to verify the processes simulated by the model. They chose thirteen parameters to represent the desired hydrological processes. Their results show that all investigated hydrological processes were well simulated. They concluded that TEDPAS is a very useful tool in verifying hydrological processes simulated by models.
Willkommen et al., 2017 applied TEDPAS to the PondR model to simulate the temporal dynamics of the internal processes within drainage ponds. An analysis of TEDPAS showed that ground water parameters were predominant throughout the whole year. Guse et al, (2013) used TEDPAS as a tool in improving the representation of hydrological processes in SWAT in Treene catchment in Germany. They selected eight SWAT parameters to represent the hydrological processes. The authors went further and used TEDPAS as a model diagnostic tool to assist in evaluating the performance of SWAT model. Their results showed a high sensitivity of three ground water parameters and one evaporation parameter. Haas et al. (2014) used TEDPAS in detection of dominant nitrate processes in ecohydrological modelling. Phases where model parameters were dominant were detected. The modeled processes which were analyzed

were runoff processes and nitrate pathways. The authors concluded that TEDPAS is useful in identifying seasonal variations of dominant nitrate pathways.

The factor prioritization setting was applied in this study to identify dominant hydrological processes. FAST was used for this research because of its computational efficiency (Cuckier et al., 1973; Cuckier et al., 1975; Cuckier et al., 1978). It converges with much fewer number of model runs compared with other methods, for example Sobol's method (Saltelli 1998; Reusser 2011). Cukier, McRae, Shuler, Petschek, Schaibly (1982) gave more information about this algorithm. The algorithm was implemented in the R package FAST using R studio (Reusser , 2008).

2.6 Base flow Separation

In order to improve the results of calibration, base flow must be separated from surface runoff. There exists different techniques for base flow separation. A number of graphical techniques can be used to define the base flow between a given starting and ending point in a hydrograph (Chow et al, 1988). The main disadvantage of such methods is that they are cumbersome and very inefficient when used in separating base flow for long periods of time. Digital filters have also been used for base flow separation. It is based on a method which was first used in signal analysis and processing in order to separate high frequency signals from low frequency signals (Lyne & Hollick, 1979). This method has been used in digital base flow separation on the basis that high frequency waves represent direct runoff while low frequency waves represent the base flow component of streamflow (Eckhardt, 2005). The SWAT base flow filter program which is a digital filter was preferred for this research. This is due to its user friendly interface and its efficiency.

2.7 SWAT model calibration and validation

A model must be calibrated and validated for it to be successfully used to perform hydrologic simulations of a catchment. There are three calibration approaches which are generally accepted by the scientific community. These are manual calibration, automatic calibration and a combination of the two methods.

SWAT has two inbuilt calibration tools. These are auto calibration and the manual calibration helper. The manual calibration helper assists in comparing measured and simulated results. The parameters are adjusted accordingly until reasonable fit is achieved. Santhi et al., (2001), recommends the following general procedure illustrated in Figure 2.2 for the manual calibration of SWAT using stream flow.

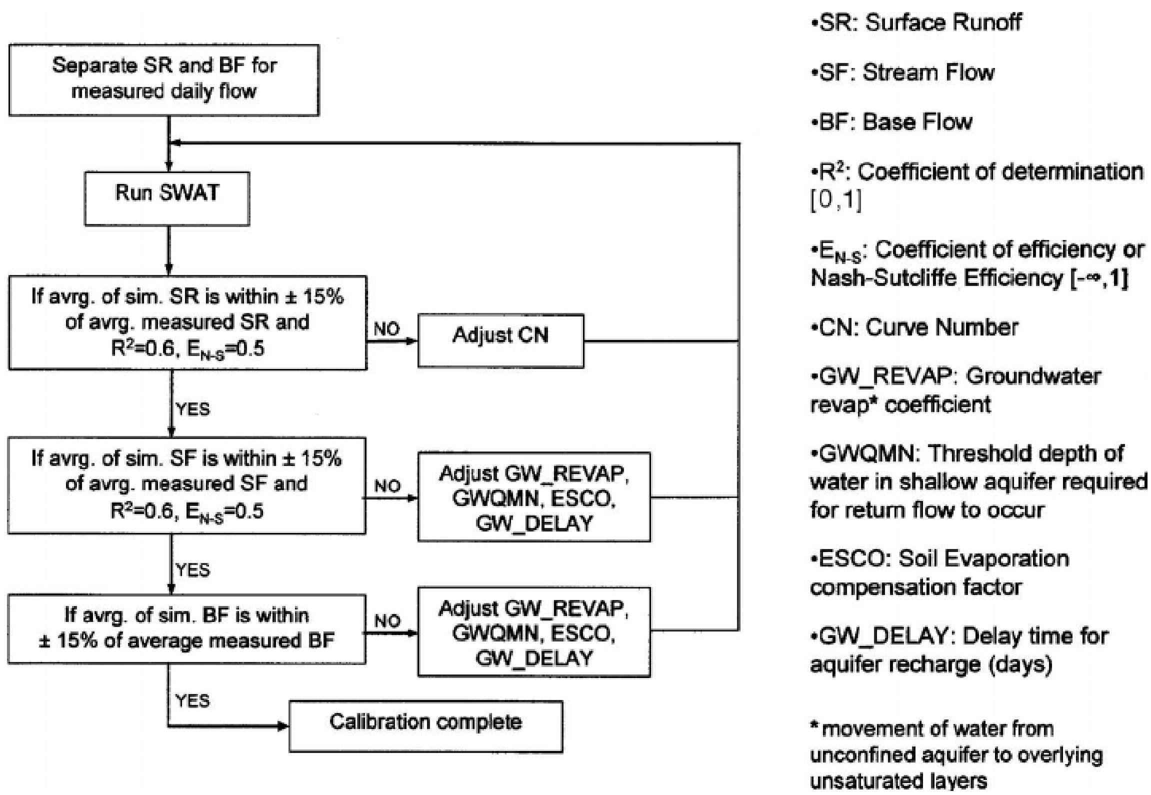

Figure 2.2 Calibration procedure for SWAT model . (Source: Santhi et al. 2001)

When the parameters to be calibrated are many, manual calibration can be cumbersome (Balascio et al.1998) hence automated procedures are recommended in such situations. As for the auto calibration option, an optimal fit of parameters is obtained based on a multi objective calibration which incorporates the shuffled complex evolution method algorithms (Green & van Griensven, 2008). SWAT-CUP is a program which combines manual calibration procedures and automated procedures while incorporating sensitivity and uncertainty analyses. The user manually adjusts the parameters and their ranges iteratively between the auto calibration runs (Arnold et al, 2012). In this study, the manual calibration was preferred.

2.8 Model Assessment

To assess the performance of a model through calibration and validation, various statistical indicators can be used. These include Nash-Sutcliffe efficiency (NSE), Standard Deviation Ration (RSR), Coefficient of determination (R^2) and Percent bias (PBIAS). NSE gives the relative magnitude of the residual variance compared to the variance of the measured data. It is an indicator of how well the plot of the observed against the simulated data fits the 1:1 line (Nash and Sutcliffe, 1970).NSE values can range from -∞ to 1. It is recommended that, NSE values should surpass 0.5 in order for model results to be considered satisfactory for hydrologic evaluations performed at a monthly time step. NSE values ranging between 0.5-0.65 are acceptable; values ranging between 0.65-0.75 are good, and values exceeding 0.75 are very good. The Nash–Sutcliffe efficiency coefficient is calculated as shown in Eq. 2.6:

$$NSE = 1 - \left[\frac{\sum_i^n (Y_i^{ob} - Y_i^{sim})}{\sum_i^n (Y_i^{ob} - Y_i^{mean})}\right] \qquad \text{Eq. 2.6}$$

where Y_i^{ob} is the *i*th observation for the constituent being evaluated, Y_i^{sim} is the *i*th simulated value for the constituent being evaluated, Y_i^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

RSR standardizes root mean square error (RMSE) using the standard deviation of the observations (Singh et al. 2004). It is calculated as shown in Eq. 2.7. The lower the RSR value, the better the simulation. RSR value equal or less than 0.7 are considered satisfactory (Moriasi et al., 2007)

$$RSR = \frac{\sqrt{\sum_i^n (Y_i^{ob} - Y_i^{sim})}}{\sqrt{\sum_i^n (Y_i^{ob} - Y_i^{mean})}}$$ Eq. 2.7

$$R^2 = \left[\frac{\sum_i^n (Y_i^{ob} - Y_i^{mean})^2}{\sum_i^n (Y_i^{sim} - Y_i^{mean})^2}\right]$$ Eq. 2.8

PBIAS is a measure of the tendency of the modeled data to be lesser or larger than the measured data. Low magnitude values of PBIAS are an indicator of accurate simulation of the model with 0 being the optimum value. Positive values mean the model is biased towards underestimation of values while negative values mean the model is biased towards overestimation (Gupta et al., 1999). It is calculated as shown in Eq. 2.9.

$$PBIAS = \left[\frac{\sum_i^n (Y_i^{ob} - Y_i^{sim}) * 100}{\sum_i^n (Y_i^{ob})}\right]$$ Eq. 2.9

Moriasi et al. (2007) set out to establish the most suitable statistical indices for model performance. Through a thorough review of model evaluation methods, the authors recommended the use of NSE, RSR and PBIAS in evaluating the performance of hydrological models.

2.9 Application of SWAT in Hydrological Modeling

In the past many researchers have applied SWAT in hydrological modeling in catchments of different characteristics. The catchments varied in land use and size. Some catchments were well gauged while some were ungauged. Zhang et al. (2008) applied SWAT in modeling the monthly runoff in a 114,345 Km^2 catchment in China while Spruill et al.(2000) used the model to simulate streamflow in a 5.5 Km^2 basin in Kentucky. Jain et al. (2017) applied SWAT in modeling the hydrology of a Himalayan basin. The model was calibrated manually using streamflow data. Their results show that lateral flow and ground water flow were the main contributors to streamflow. ET and water yield varied between 57-58% and 43-46% of the received precipitation.

Boupha et al., (2015) used the SWAT model to simulate water balance in Xebanghieng (XB) basin. The modeling of the water balance was performed at an annual, monthly and daily time step using weather and spatial data. The performance of the model during calibration was good. Shawn (2014) used SWAT to simulate the hydrology and water quality of Military landscapes in Gagetown. The model performance in simulating three partial years of daily stream flow ranged from satisfactory to good. Ndomba, (2008) applied the SWAT model in a data scarce catchment in Tanzania known as Pangani River catchment. The runoff component of the model showed that similar sets of important parameters were obtained through sensitivity analysis by using observed data or without it. Ramos et al., (2015) modeled hydrological processes in an ungauged agricultural land in the Mediterranean using SWAT model. The model predicted runoff and soil water satisfactorily. Easton et al., (2010) applied SWAT in predicting runoff and sediment losses in the Ethiopia Blue Nile basin. The results showed that runoff increased with increase in rainfall especially during monsoon seasons. The authors recommended that focusing on small areas where runoff is produced can be a very effective way of protecting water resources and controlling erosion.

2.10 Impact of Land Use Change on Basin Hydrology

Land use/ Land cover has a great influence on the hydrology of a catchment. The impact of land cover influences the distribution of water and the mean annual runoff. Impacts on low flows and peak flows are significantly important. Influence of land cover on overland flow depends on a number of factors such as the plant’s ability to intercept rainfall/moisture, amount of water a plant loses through transpiration and the ability of the soil to hold water. Changing the land cover to a plant that loses a lot of water through evapotranspiration will lead to a reduction of stream flow (Yehayis, 2010).

Urbanisation also has an effect on the hydrology of a catchment. Destroying natural depressions which could have stored runoff, constructing surfaces which are impervious and deforestation change how a catchment responds to rainfall events. This can lead to increased runoff and sedimentation (McColl, 2007). Reduction of infiltration capacity of soils through compaction leads to increased peak flows which might result in flash floods.

A number of studies have been conducted to determine the impacts of land use changes on the hydrology of a catchment. Researchers applied different hydrological models to simulate hydrology. Some researchers used land use change models to generate scenarios while others used hypothetical scenarios. Fohrer et al (2005) used the Proland and IOSWAT models to assess the effects of different agriculture field sizes on the hydrology of the Aar catchment in Germany.

Bithell and Brasington (2009) investigated how demographic changes influence deforestation in a catchment in Nepal. The results show that the reduction of forests resulted in a 4% increase in total evaporation, a reduction of 22% in annual discharge and an increase of 18% in loss to deep ground water and internal storage of the soil. Du et al (2012) used a land use change model together with HEC-HMS model. The HEC-HMS model is a single event, lumped, empirical-conceptual based model which uses a quasidistributed method to calculate runoff. Future land use scenarios were generated using Cellular Automata Model and Markov Chain. The authors overlaid the urbanization simulated spatial data of the year 2018 to a base map of 1988 to simulate the runoff generated upto the year 2018. The results show that urban areas increased from 3% in 1988 to 31% in 2018. The daily peak flows of selected floods also increased from 2.3% to 13.9%. The authors concluded that combining a distributed hydrological model with a dynamic land use change model is effective in evaluating the impacts of urbanization on the hydrology of a catchment.

Lin et al (2007) used a lumped distributed hydrologic model combined with a spatially explicit land use change model CLUE-s to determine the impacts of land use change on the hydrology of Wu-Tu catchment in northern Taiwan. The authors concluded that combining a hydrologic model with a spatially explicit land use simulation model is an effective tool of determining land use change impacts on the hydrology of a catchment.

It also assists in development of landscape decision support system for land use planning of a basin, its management and development of policies.

Chu et al (2010) also used CLUE-s in the same catchment but combined it with DHVSM a physically based distributed hydrologic model. The authors concluded that the spatial distribution of hydrological parameters greatly influence the hydrological processes in a catchment. The consequently recommended the use of distributed hydrological models when assessing impacts of land use changes on the hydrology of a catchment. Niehoff et al (2002) used LUCK a spatially distributed land use change model to create different scenarios of land use. They increased different land uses by various percentages and investigated the impacts of those changes using a distributed hydrological model known as Wa-SIM-ETH. The authors found that a combination of the two models has a great potential in hydrological modelling.

Bormann and Elfert (2010) used the Wa-SIM-ETH model to model hydrological processes in a lowland catchment in Germany. They used the Integovernmental panel on Climate Change (IPCC) to create future land use scenarios and determine their impacts on the hydrology of the catchment. They found the model to be hardly sensitive to slight past changes when investigating historical land use changes. However, scenarios which involved increase in agricultural land had significant effects on the water flow. The authors recommended that when investigating the impacts of changes of land use, different land uses should be investigated instead of focusing on one.

Oogathoo (2006) evaluated the impacts of different management scenarios on the hydrology of Canagagigue creek watershed in Ontario Canada using a physically distributed model known as MIKE-SHE. Different land uses were increased or decreased and their impacts on the hydrology assessed. The author emphasized the usefulness of MIKE-SHE in simulating management practices.

SWAT has been used in many parts of the world to assess impacts of land use change on the hydrology of a catchment (Jha & Gassman 2014, Neupane & Kumar 2015, Johnson et al., 2015). Researchers used different land use scenarios such as increasing agricultural land, changing crop rotations and converting one land use change to another

(Schilling et al., 2014). Githui et al (2009) assessed the past and potential future environmental changes using SWAT, and their impact on the hydrology of the Nzoia Catchment .Results showed that runoff was highest from agricultural lands, followed by shrubland, grasslands and forest.

Odira et al (2010) aimed to simulate the streamflow changes as a result of the land-use/cover status in Nzoia catchment using SWAT. Between 1973 and 1986 there was a decrease of 48.3% in forest cover. The agricultural area decreased between 1973-1986 with 22.4% and 1986-2000 and 4.6%.The simulated scenarios were compared to the baseline scenario. All scenarios gave an increase in discharge during wet months and a decrease during dry months. Psaris (2014) used SWAT to assess the sensitivities of stream flow in two urbanizing watersheds in Northwest Oregon, USA to various climate and urbanization scenarios. The results showed that increasing urban areas led to an increase in surface runoff.

2.11 Coordinates systems

Every data set possesses a coordinate system which is used to incorporate it with other geographic datasets which have the same coordinate system. There are two types of coordinate systems; geographical and projected coordinate systems. Geographical coordinates systems use longitudes and latitudes to reference points. This means that the distance between two longitudes will change as you move towards the north and south poles. Projected coordinate systems on the other hand offer mechanisms which transform maps which were in the earth's spherical form into a two dimension plane. Projected coordinate systems include universal transverse Mercator (UTM), Robinson or Albers Equal Area.

2.12 Previous Hydrological Studies in Chania catchment

A number of researchers have conducted hydrological studies in the Chania catchment. Gathenya (1999) applied water balance models for management of the catchment. Kigira et al., 2007 investigated the effects of land use change on sediment yield. Due to issues of land degradation, impacts of soil and water conservation practices on ecosystem services on the upper part of Chania catchment have also been studied (Mwangi, 2011 and Mwangi et al.,2015). Gathangu et al., modeled the impacts of structural conservation measures on water and sediment yield. No studies have ever been conducted on the impacts of land use change on the water balance components of Chania catchment. This current study seeks to address this gap in order to make recommendations on the best land use practices to improve the management of the catchment and to curb water shortage problems.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter presents the methodology that was undertaken to achieve the specific objectives of this research.

3.2 General research design

The approach used to conduct this study is summarized in Figure 3.1. This approach review, application of TEDPAS to the SWAT model to determine the temporal variability of hydrological processes, calibration and validation of the model and model simulation using different land use scenarios.

3.3 Materials and methods

The following data required to run swat model was collected from the sources indicated in Table 3.1.

3.3.1 Digital Elevation Model

A Digital Elevation Model (DEM) with a 30m resolution defined the topography of the area of interest. It was acquired from Regional Centre for Mapping Resource for Development. It described the elevation of any point at a given location and specific spatial resolution as a digital file. It is used by SWAT model to delineate the watershed in to a number of sub basins based on elevation. Drainage pattern, slope and stream length within the watershed are processed using DEM. The DEM was projected to UTM 37S and clipped before use.

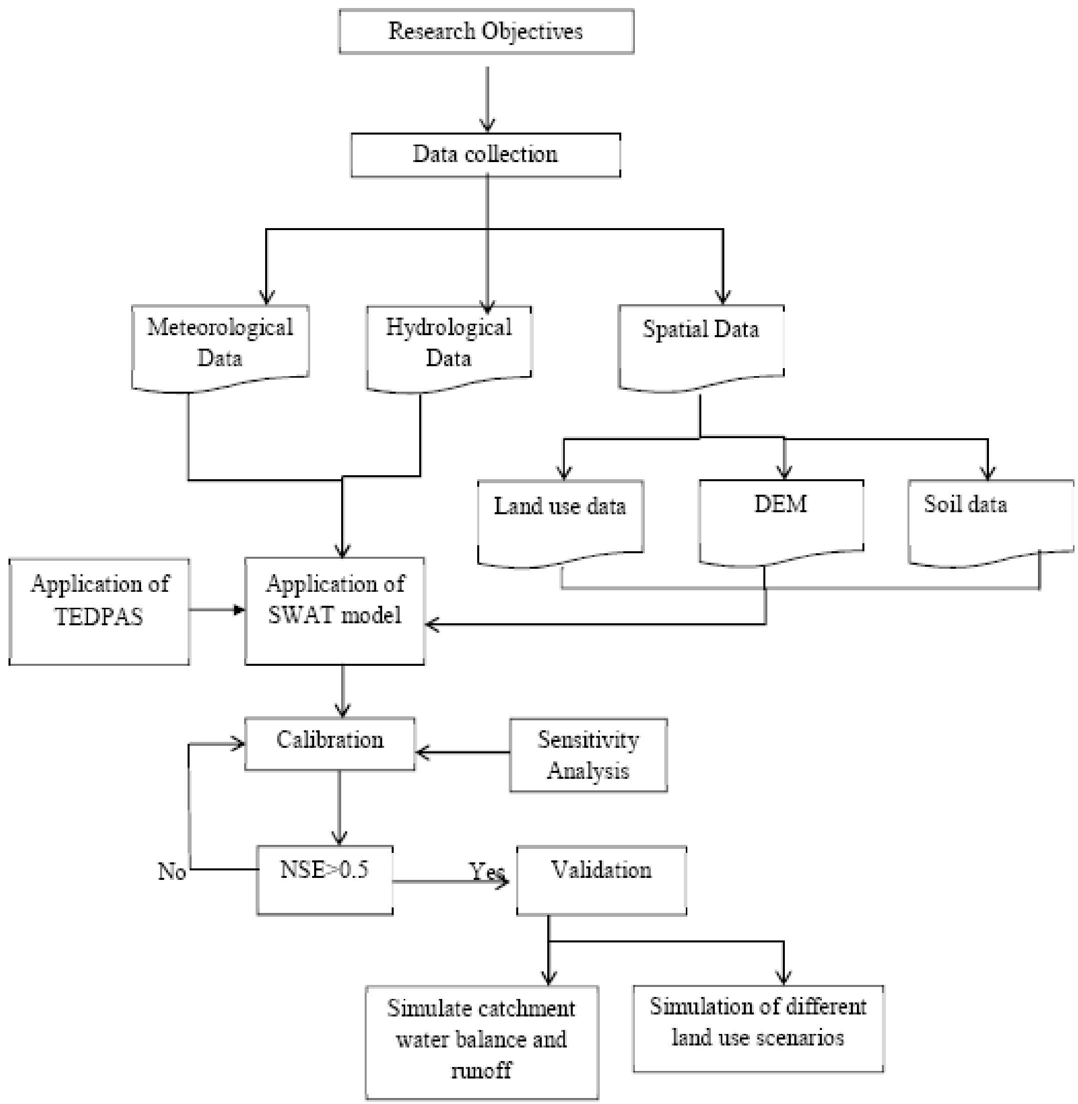

Figure 3.1: Flow chart showing the general methodology followed in the research.

Table 3.1 Data used to run SWAT

Data	Description	Source
Spatial	Digital Elevation Model 30m resolution	Regional Centre for Mapping Resource for Development;
	Soil Map 1:1000000 resolution	International Soil Reference and Information Centre
	Land use/ Land Cover Map 30m resolution	Food and Agriculture Organization 2000 dataset
Meteorological 2000-2008	Precipitation	Recording stations in and around the catchment, Kenya Meteorological Department
	Minimum Maximum Temperature	Kenya Meteorological Department, Weather stations within the catchment
	Relative Humidity	"
	Solar Radiation	"
	Wind Speed	"
Stream flows 2000-2008	Daily/ Monthly stream flows	Gauging stations in the catchment/ WRMA

3.3.2 Land Use Map

An existing FAO land use map with a 30m resolution was used as the input land use map. It was projected to UTM 37S. Table 3.2 shows areas under each type of land cover. The main land uses were forest, agriculture and shrubs. Forest cover comprised about 36% of the catchment, Agriculture comprised around 19% of the catchment and shrubs comprised 12% of the catchment. The balance comprises of a mixture of various land uses as indicated in Table 3.2. FAO land cover maps have successfully been used in hydrological modeling by other researchers (Olang' et al., 2011 and Nkonge et al., 2014)

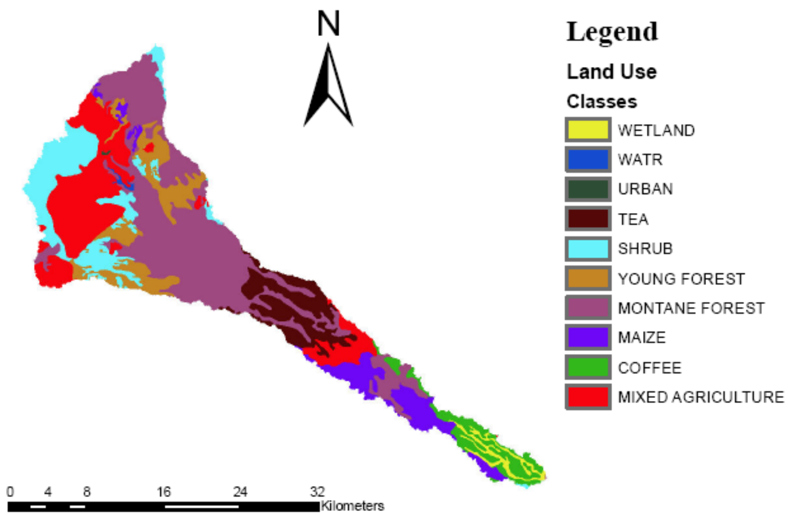

Figure 3.1 ***Land*** **Use FAO Africover (2000)**

Methodology used in classifying FAO Africover Land use maps

The FAO Africover land use map is prepared by its developers using remote sensing data and GIS. The land cover is derived by visually interpreting high resolution satellite images after digital enhancement. It is based on a homogenized and hierarchical classification system known as Land Cover Classification System, LCCS. Existing topographical maps are used to derive geographic reference. Updates are made from remote sensing and ground truthing and surveys which are geo-referenced form GPS points. The chosen geometrical base which is used as a reference is dependent on the quality of topographic map and the geodetic network. The geometrical base is either the existing topographic maps or satellite images geocoded with GPS measurements using spatio-triangulation techniques.

Table 3.2 - Area under each Land Use for the Africover Map

Land Use	**Area(km^2)**	Percentage
Forest	192.04	35.97
Coffee	26.75	5.01
Shrubs	67.51	12.64
Tea	44.23	8.28
Wetland	8.83	1.65
Urban	0.24	0.05
Maize	38.39	7.19
Water	1.03	0.19
Mixed Agriculture	105.56	19.8
Young Forest	49.24	9.22

3.3.3 Soil data

The Kenya Soil and Terrain database (KENSOTER) from International Soil Reference and Information Centre (ISRIC) was used to derive soil characteristics of the area. A shape file containing the different soils in the area was used during modeling. It had a 1:1000000 resolution. Soil properties such as Bulk density, Available Water Capacity and hydraulic conductivity were calculated using the Soil-Plant-Atmosphere-Water (SPAW) Model.

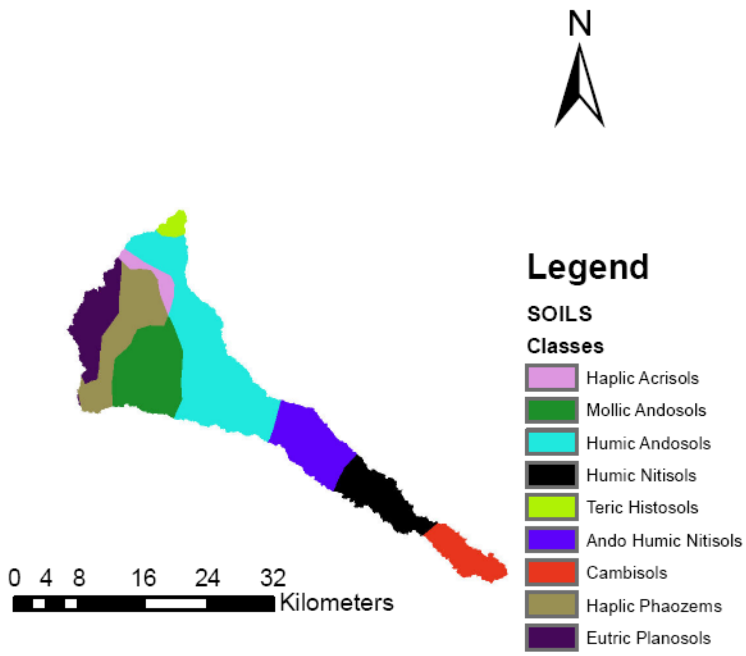

Figure 3.2 **Soils in Chania catchment**

3.3.4 Weather data

The following Table 3.3 shows weather data from stations in the catchment. The weather data includes rainfall, wind, temperature and solar radiation. Rainfall and temperature data from Thika Agromet and Thika dam were the only ones used during simulation because they had fewer gaps. In addition to that, they also had the most recent data of a similar period. Data from Kimakia forest and Thika Agromet were used to create the wgn files. The weather generator facilitated simulation of missing data and filling of data gaps.

Table 3.3 Location and Period details for weather stations.

STATION	LATITUDE	LONGITUDE	PERIOD AVAILABLE	PERCENTAGE MISSING
Kimakia Forest (9036233)	0^0 46’ 00’’S	36^0 45’ 00’’E	**1954-1984**	**12**
Thika Dam (9036344)	$0^0$49’10’’ S	36^0 51’ 07’’E	**1996-2010**	**6**
Thika Agromet (9137048)	$1^0$01’26’’ S	37^0 04’ 04’’E	**1996-2014**	**11**

3.3.5 Streamflow data

The following Table 3.4 shows data available for River Gauging Stations in the catchment. RGS 4CA02 was used for calibration and validation because of the quality of data it has and its location at the outlet of the catchment. Data from 2000-2008 was used for calibration and validation as it had few gaps.

Table 3.4 Location and period details for River gauging Stations

S/ID	RIVER	LATITUDE	LONGITUDE	PERIOD OF DATA AVAILABLE	PERCENTAGE MISSING
4CA09	KIMAKIA	$0^0$46’10’’ S	36^0 44’ 40’’E	8/10/1956-7/31/1998	41
4CA11	KIMAKIA	$0^0$45’50’’ S	36^0 44’ 40’’E	8/10/1956-4/30/1999	37
4CA14	KIMAKIA	$0^0$45’40’’ S	36^0 44’ 25’’E	6/10/1958-3/31/1996	27
4CA20	MAKIAMA	$0^0$45’00’’ S	36^0 43’ 35’’E	10/15/1964-3/31/1996	28
4CA02	CHANIA	1^0 01’ 27’’S	37^0 03’53’’E	1/1/1956-12/30/2008	19

3.3.6 Input data preparation and Model Setup

Meteorological data was converted to dbf format which is compatible with SWAT. Soil database and Weather generator for local conditions were created using local data for Chania catchment. This was added to the SWAT database. After all inputs were prepared, they were loaded into the SWAT model as per the SWAT 2009 manual. Look up tables for soil and land use were prepared in dbf format. Watershed delineation, HRU analysis and writing of input tables were done. This resulted in 35 subbasins as shown in Figure 3.4. The option of multiple HRUs was selected leading to a total of 647 HRUS. 0%, 0%, 0%, threshold was used to capture all land use, soil and slope. This option was preferred to ensure the representation of land uses with small percentages in the modeling process and in the output as done by Chiang et al., 2010. The model was run from the year 2000 to 2008 with the first year being used for model warm up. Warming-up the model is an essential part of the simulation process to promote the stability of the basic flow conditions. This allows for the simulations following the warm up period to achieve an equilibrium of hydrological processes.

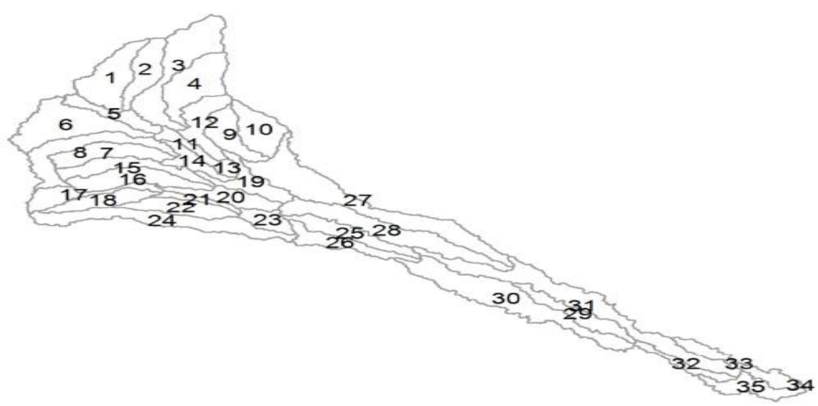

Figure 3.3: Subbasins delineated by SWAT model

3.3.7 Sensitivity analysis for Calibration

Sensitivity analysis was performed in order to gain a better understanding of parameters required for calibration of SWAT for use in Chania catchment. Sensitivity of hydrologic parameters in SWAT is greatly influenced by a number of factors such as size of catchment, land use variations, topography and geomorphological characteristics of the area. The sensitivity of parameters for calibration purposes was analysed using a combination of Latin Hypercube method and the one-factor-at-a-time (OAT) method proposed by Van Griensven and Meixner (2006). It is inbuilt in the SWAT model. This method ensures the whole range of parameter space has been sampled while incorporating the precision of an OAT design. Finer details of this procedure can be found in SWAT 2005 (van Griensven, 2005). Table 3.5 shows the selected parameters, their ranges and iteration method applied during the sensitivity analysis as done by Rial-Rivas et al., 2011. The model was run from the year 2000-2004 using default values for the parameters. The parameters were varied within the upper and lower boundaries indicated in Table 3.5. Three methods of variation were used for the sensitivity analysis. The first method involved replacing the initial value with a different value. The second method involved adding a given value to the initial value. The third method involved multiplying the initial value by a given figure.

Table 3.5 Parameters selected for sensitivity analysis

PARAMETER	LOWER BOUNDARY	UPPER BOUNDARY	ITERATION METHOD
Alpha BF	0	1	1
Canmx	0	10	1
CH_K2	0	150	1
CH_N2	0	1	1
CN2	-25	25	3
EPCO	0	1	1
ESCO	0	1	1
Gw_delay	0.001	10	2
Gw_Revap	0.001	0.036	2
Gwqmn	0.001	1000	2
Revapmn	0.001	100	2
Sol_Alb	-25	25	3
Rchrg_dp	0	1	1
Sol_AWC	-25	25	3
Sol_k	-25	25	3
Sol_Z	-25	25	3
Surlag	0	10	1
Biomix	0	1	1
Slope	-25	25	3
Slsbsn	-25	25	3

1-Replace value, 2-add to value, 3-Multiply by value %

3.2.6 Base flow Separation

The stream flow data was separated into surface flow and base flow using the SWAT Bflow filter program. This base flow filter program offers the user a web interface in order to determine the runoff/stream flow fraction. It also allows the user to determine the value of alpha factor to be used in the SWAT ground water files. The algorithm used in this automated digital filter was adopted from Arnold and Allen (1999). It is based on the equation below

$$q_t = \alpha q_{t-1} + \frac{1+\alpha}{2}(Q_t - Q_{t-1})$$

where, q_t is the filtered direct runoff at the t time step(m^3/s);q_{t-1} is the filtered direct runoff at the t-1 time step (m^3/s);α is the filter parameter; Q_t is the total stream flow at the t time step (m^3/s); and Q_{t-1} is the total stream flow at the t-1 time step (m^3/s).
Local stream flow data from RGS 4CA02 was uploaded on the web interface found at (Google map based WSAT Bflow system, n.d).

The baseflow filter program was run and the results were saved using excel sheets.

3.4 Calibration and Validation

The model was calibrated using stream flow data from RGS 4CA02 which is along Chania river. Calibration was done from the year 2001 to 2004. Selected parameters which were chosen based on literature and sensitivity analysis were varied and adjusted with the aim of getting the best fit between observed and simulated values. Based on recommendations by Moriasi et al., 2007 and the high frequency of use by other researchers (Gassman et al., 2007) three statistical indices NSE, PBIAS and R^2 were selected to assess this fit. Goodness of fit was used to assess the performance of the model. A general visual agreement between simulated and observed data is an indication of adequate calibration and validation (Singh et al., 2004).

The methodology adapted in this research for calibration of the model was similar to the methods used or recommended by other researchers (Shawul et al., 2013; Da Silva et al.,2015; Feyereisen et al.,2007; Kigira et al., 2007; Serfas, 2012). A study by Van Liew et al., 2005, shows that for few calibration parameters, manual calibration outperformed automatic calibration methods making it the preferred choice for this study. An iterative approach was used for the manual calibration of the model. After successful setting up of the model using the input data, the model was run. The values of the simulated discharge were then compared to the values of observed discharge. To assess if reasonable results had been achieved, NSE, PBIAS and R^2 statistical indices were used to evaluate the performance of the model. If the results were not reasonable, the parameters were adjusted within reasonable ranges of values stated in the SWAT user manual. This process was repeated until the simulation with the best results was achieved. Parameterization of the plant module was also conducted. This was done achieved by adjusting values of LAImx.

The first step in the manual calibration involved calibrating the surface flow component of the total average annual water yield. This was achieved by adjusting the runoff CN2. Table 38.5 from the SWAT manual (Arnold et al., 2011) was constantly referred to to ensure the modified CN2 values were always within acceptable ranges. The next step involved adjustment of Gwqmn, Revapmn and SOL-AWC to closely match simulated and observed base flow. Once a reasonable proportion of surface flow to base flow was achieved, ESCO, SOL-Z and ALPHA-BF were adjusted with the aim of maximizing NSE.

To demonstrate that the model is capable of making accurate predictions (validation), the output of the model was compared to observed stream flow for the year 2005-2008 without further adjustment of the parameters. The values of the output of the model were compared to the values of observed stream flow using excel. Evaluation of the results was done using NSE, PBIAS and R^2.

3.5 Determination of hydrological processes governing the temporal variability of stream flow.

The methodology used to achieve this objective was similar to the methods adapted by Guse et al., (2016) and Pfannerstil et al.(2015). The basis of this methodology is that information about the simulated hydrologic process dynamics can be acquired by use of temporal sensitivities of the respective model parameters. To achieve this objective, temporal dynamics of parameter sensitivity (TEDPAS) was analyzed to identify the hydrological processes which were simulated.

Eight different SWAT parameters shown in Table 3.6 were chosen to represent different hydrological processes. Figure 3.5 shows the hydrological processes governing the variability of stream flow while Figure 3.6 shows the model parameters which represent those processes. The dominance of a hydrological process at a given time is reflected by the corresponding sensitivity of the model parameter. The Fourier Amplitude Sensitivity Test (FAST) algorithm was used to determine the global sensitivities of model parameters within the required period as done by Guse et al. (2013). This was done using the R programming language in R studio. Table 3.6 shows SWAT parameters and the ranges . Surlag regulates the portion of total available water that will be able to enter the river reach on any given day. SOL_AWC is used to estimate the field capacity for each soil layer. It influences the calculation of the percolation which takes place in the current soil layer. Two ground water parameters, Groundwater time delay, GW_DELAY, and base flow recession constant, ALPHA_BF control the retention of the water in the soil passing through the groundwater to the river reach. The GW_DELAY is measured in days and it regulates the time delay for recharge of the shallow aquifer. The recharge resulting from percolation is distributed into two aquifers. The aquifer fraction coefficient (RCHRG_DP) determines the splitting of recharge between the shallow and deep aquifers. CANMX represents the water capacity of the canopy storage. The canopy storage is dependent on the leaf area index of the crop represented by the land cover. Precipitation water only reaches the soil after the canopy storage is filled completely (Neitsch et al 2011).CANMX is also included in the calculating the actual evapotranspiration. ESCO is a parameter representing evaporation from the soil. Evaporation losses from the soil occur only after canopy storage has been emptied (Neitsch et al., 2011).

Table 3.6 Selected model parameters and their ranges

Parameter	Parameter Description	Process	Lower Boundary	Upper Boundary	Type
CN2	Curve Number	Surface runoff	-15	15	**Add**
Surlag	Surface Runoff Time Lag	Surface runoff routing	0.1	2	**Range**
Canmx	Maximum Canopy Storage	Interception	0	4	**Add**
ESCO	Soil Evaporation Compensation Factor	Evapotranspiration	0	1	**Range**
SOL_AWC	Available Soil Water Capacity	Soil	-0.01	0.2	**Add**
Rchrg_dp	Aquifer Fraction Coefficient	Ground water	0	0.3	**Range**
Gw-delay	Groundwater Time Delay	Ground water	2	30	**Range**
Alpha_BF	Baseflow Recession Constant	Ground water	0.01	0.2	**Range**

For FAST, 8 parameters required 243 model runs. The 243 FAST parameter sets were generated using the fast_parameters function described in Reusser, 2015. SWAT was run 243 times for each unique parameter set from the year 2000-2004 with the first year being used for model warm up. The SWAT model output for all 243 runs was returned to R and used to generate the sensitivities using the sensitivity_rep function also described in Pfannerstill, Guse,Reusser, and Fohrer (2015). The output of the temporal sensitivity analysis was saved in Excel in csv format. The temporal sensitivities were compared, visually using graphs, to the stream flow hydrograph generated at RGS 4CA02. The segments of the hydrograph were generally categorized into four parts; peak, recession, low flow and re-saturation periods as done by Guse et al, 2013. The sensitivities were also compared to different magnitudes of flow by use of flow duration curves (Guse et al, 2016). This was done in order to determine which parameters are dominant in each of the different discharge magnitudes. The FDC was divided into five segments: 0-5%, 5-20%, 20-70%, 70-95% and 95-100% (Pfannerstil et al, 2014). The parameter sensitivities were averaged at a monthly scale in each FDC segment.

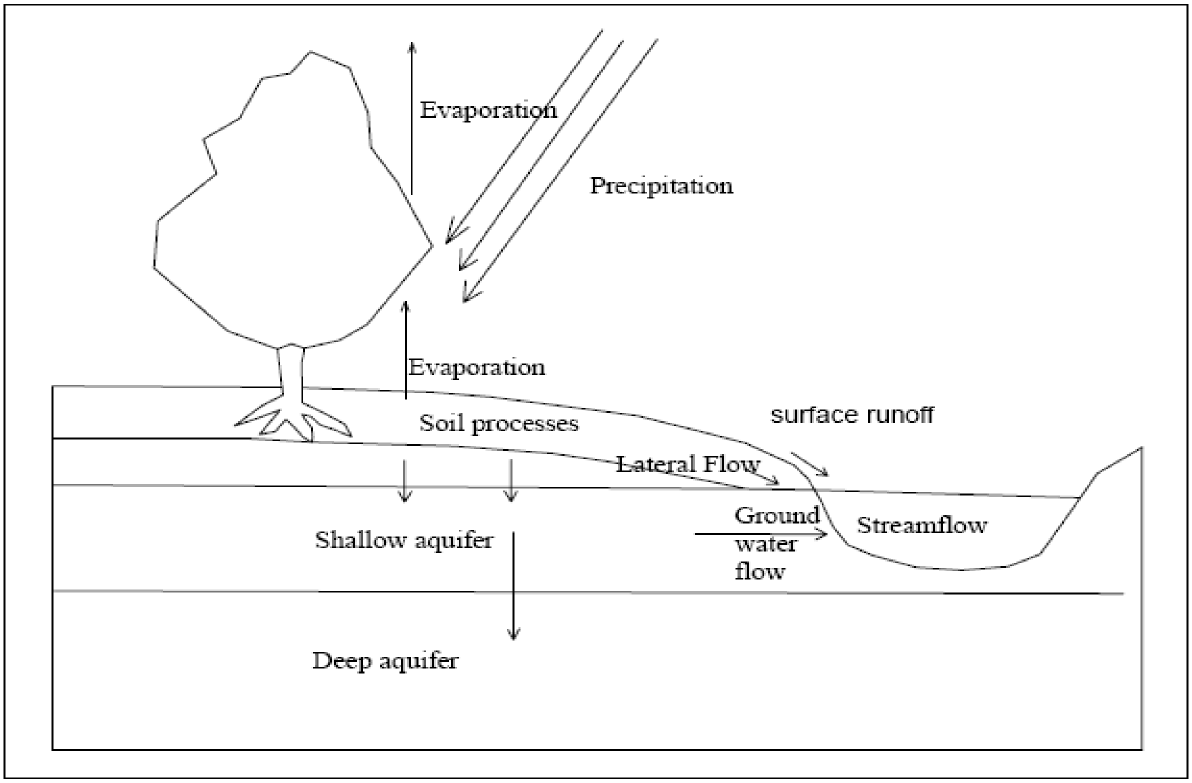

Figure 3.4 Hydrological Processes governing variability of stream flow (Modified from Neitsch et al., 2005

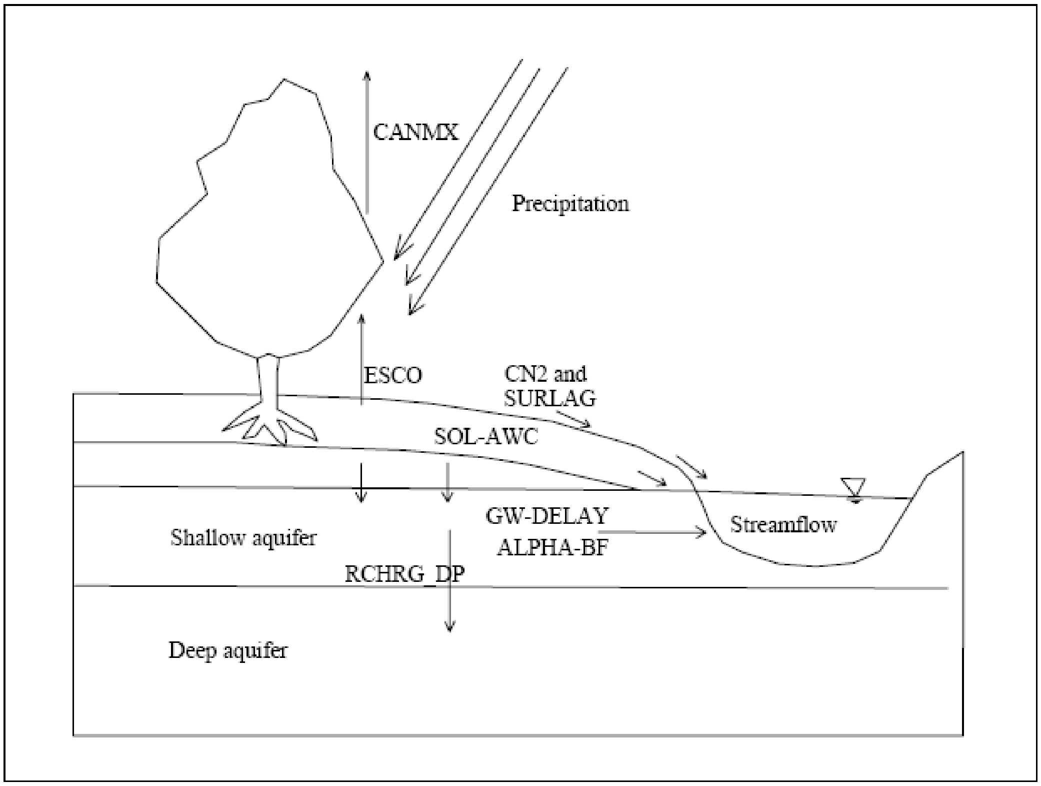

Figure 3.4 Selected parameters representing different hydrological processes (Modified from Neitsch et al., 2005)

3.6 Determination of Spatio-Temporal variability of water balance components.

The determination of the spatial and temporal variability of water balance components was achieved using SWAT model following a similar methodology adopted by Shawul et al, 2013. After the SWAT model was successfully calibrated, it was run on a monthly time step from the year 2000-2008. The first year of the simulation was used for warm up in order to establish equilibrium conditions. The spatial variation of precipitation, surface runoff, ground water, ET, lateral flow and water yield were each determined by calculating the annual averages for each of the subbasins in the watershed as done by Yin et al., 2016. . The water balance was determined based on equation 3-1

$.P = ET + LATQ + GW + SURQ + \Delta SW\ storage + LOSSES$….Eqn 3-1

Where P is Precipitation in mm, ET is evapotranspiration in mm, GW is ground water in mm, LATQ is lateral flow in mm and Δ SW storage is change of soil water storage in mm.

Annual average values of precipitation, ET, surface runoff, ground water, lateral flow and water yield were each embedded to the attribute table of the watershed map. This was done in ArcGIS. The results were presented by using maps of the Chania subcatchment which contained the modeled subbasins. Colour ramps representing different value ranges were used to visually display the variation of ET, surface runoff, ground water, lateral flow and water yield spatially across the sub basins.

In order to determine the temporal variability of water balance components, the quantities of the water balance components were extracted from the output files for the baseline period for the years 2001-2008. The water balance components from all the 647 HRUs in the whole catchment were extracted. The temporal variability was first determined at an annual scale. The annual average values of precipitation, evaporation, ground water, surface runoff and lateral flow were each determined for each year for the year 2001 to 2008. The results were presented by use of graphs in order to display their variability over the years. Secondly, the variability of the same water balance components were determined at a monthly scale in order to establish their variability over the seasons. This was done by calculating the monthly averages. These results were also presented by use of graphs for each water balance component.

3.7 Determination of effects of Land Cover change on Water balance

The calibrated set of parameters was used for the baseline scenario (2001-2008) to provide a consistent basis to compare the baseline to the scenarios. In order to investigate the effects of Land cover change on water balance components, different hypothetical scenarios were simulated by adjusting the percentages of different land uses and compared to baseline conditions as done by Mango et al., (2010) and Can et al., (2015). This was achieved by adjusting HRU fractions, a similar methodology adapted by other researchers (Chen et al, 2016; Piniewski, 2014; Querner et al, 2013). HRU fractions were modified using the Land Use Update tool. This tool allows the user to make changes in the percentages of the land use by modifying the HRU_FR parameter. The HRU_FR parameter defines a fraction of a HRU for a given sub basin. The total sum of HRU_FR over all the HRUs within a particular sub-basin is equal to 1. Any modification of HRU fraction is only possible if the land uses being modified are all within the same sub-basin. The scenarios shown in Table 3-7 were created to investigate effects of land use change on the water balance. These scenarios were formulated based on trends and use by other researchers (Mango et al., 2010 & Kigira, 2007).

Table 3.7 Scenarios for investigation of effects of land cover change on water balance

SCENARIO	**CHANGE**
Scenario I- CDA	Conversion of 100% forest cover to agriculture in 21 subbasins where both land covers were present.
Scenario II-PDA	Conversion of 50% of forest cover to agriculture in 21 subbasins where both land covers were present.
Scenario III PDS	Conversion of 50% of forest cover to shrub land in 21 subbasins where both land covers were present .
Scenario IV-Urbanization	Conversion of 100% of shrubland to urban land in 3 subbasins where both land covers were present .
Scenario-V afforestation	Conversion of 25% of shrubland and agriculture to forests in 25 subbasins where the three land covers were present.

The model was run under each formulated scenario. Average values of ET, surface runoff, ground water, lateral flow and water yield water for the base scenario and each of the five scenarios were determined from the model output .The change in each water balance component was expressed as a percentage increase or decrease in value from its original value in the baseline scenario.

CHAPTER FOUR

RESULTS AND DISCUSIONS

4.1 Introduction

This chapter contains the results of this research and their discussion. The results are broadly divided into four parts for each of the specific objectives of this research. The section 4.1 contains results for base flow separation, sensitivity analysis for calibration purposes and calibration and validation results. Section 4.2 contains the TEDPAS results which were used as a tool to identify dominant hydrological processes. Section 4.3 contains the results of the spatio-temporal variability of water balance components. The last section 4.4 contains results of how the simulated land use change scenarios affect the hydrology of the Chania catchment.

4.2 Calibration and Validation of SWAT

4.2.1 Separation of Base flow

The base flow was separated from the stream flow using the base flow separation program. The results are shown in Figure 4.1 and Table 4.1. The alpha factor is the base flow recession constant while base flow days are the number of days it takes for the base flow recession to decline through one log cycle. The alpha factor suggested by the base flow separation program was used during the calibration of the model. The base flow separation program uses three passes to separate base flow; Pass 1, Pass 2 and Pass 3. Arnold and Allen (1999) did a comparison of published base flow values from a number of studies. Most of the values fell between Pass 1 and Pass 2.

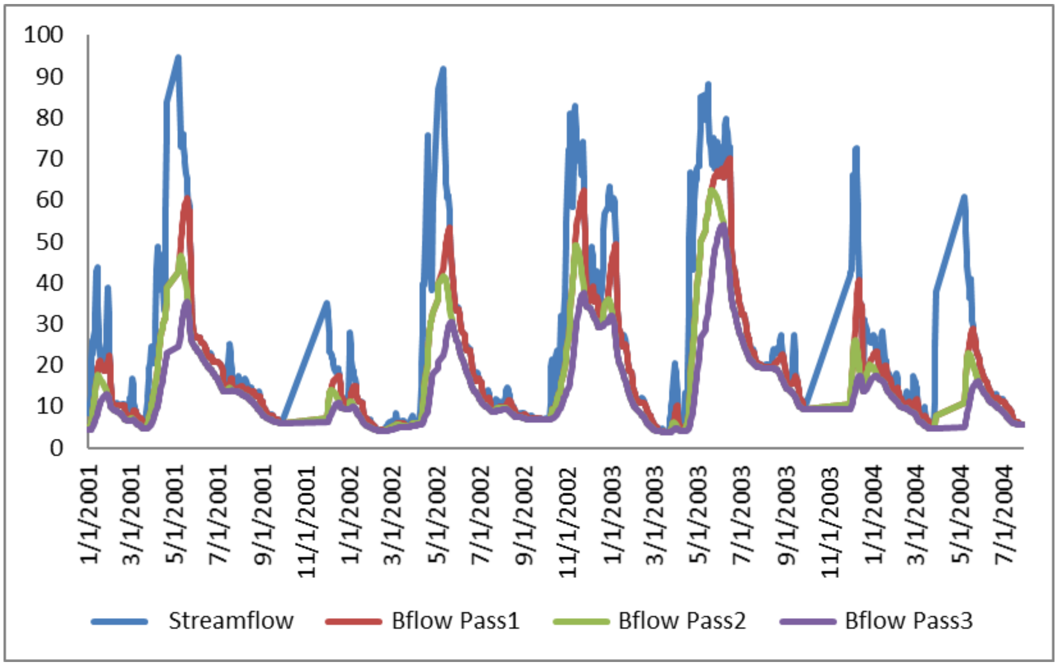

Figure 4.1 Hydrograph of stream flow and base flow estimate during pass 1, 2 and 3 at RGS 4CA02, Chania River

Table 4.1 Baseflow Separation Results

Gauging Station	Base flow (Pass1)	Base flow (Pass2)	Base flow (Pass3)	Alpha factor	Base flow days
4CA02	0.8	0.69	0.60	0.0396	100

The average of the first pass and second pass was used to separate base flow from surface flow resulting in a value of 0.745. These results mean that 74.5% of the stream flow in Chania catchment at RGS 4CA02 is contributed by base flow. This means that 25.5% of the stream flow is as a result of surface runoff. From Figure 4.1, the maximum amount of base flow occurs in the months of May and June. This is attributed to the long rains which occur during the months of March, April and May. These values are comparable to results gotten by Githui, et al 2009. Values for base flow gotten by Githui et al, 2009 from an upstream gauging station in Nzoia catchment were 0.79(Pass 1), 0.67 (Pass 2) and 0.60 (Pass 3).

From the SWAT manual, ALPHA-BF is a parameter used as an index of how ground water flow responds to changes in recharge (Smedema & Rycroft, 1983). It is an indicator of the rate at which ground water enters stream flow. Values ranging between 0.1-0.3 indicate the land has a slow response to recharge. Values between 0.9-1.0 indicate that the land responds rapidly to recharge (Arnold et al, 2010). From Table 4.1, the ALPHA-BF value from the base flow separation results is 0.0396. Low values of ALPHA-BF generally indicate very slow drainage (Arnold et al, 1995). This implies that the Chania catchment has a slow response to recharge.

4.2.2 Sensitivity Analysis Results

The results of the sensitivity test for calibration are shown in Table 4.2. Curve number is the most sensitive parameter while the average slope length is the least sensitive parameter. CN2 is a parameter which is used in the calculation of runoff. This means that runoff process is most sensitive for the calibration process implying a slight modification in CN2 will result in a greater variation of the discharge.

Table 4.2 Parameter Sensitivity Ranking

Parameter code	Rank	Parameter description
Cn2	1	Initial SCS CN II value
Esco	2	Soil evaporation compensation factor
Gwqmn	3	Threshold depth of water in the shallow aquifer required for return flow to occur
Revapmn	4	Threshold water in the shallow aquifer for revap to occur
Sol_Z	5	Soil depth
Sol_Awc	6	Available water capacity
Alpha_Bf	7	Baseflow alpha factor
Gw_Revap	8	Groundwater revap coefficient
Ch_K2	9	Channel effective hydraulic conductivity
Slope	10	Average slope steepness
Canmx	11	Maximum canopy storage
Sol_K	12	Saturated hydraulic conductivity
Epco	13	Plant uptake compensation factor
Ch_N2	14	Manning's n value for main channel
Surlag	15	Surface runoff lag time
Gw_Delay	16	Groundwater delay
Rchrg_dp	17	Deep Aquifer percolation coefficient
Biomix	18	Biological mixing efficiency
Sol_Alb	19	Moist soil albedo
Slsubbsn	20	Average slope length

These results are consistent with the results of other researchers who performed sensitivity analysis of SWAT parameters for calibration purposes. Nkonge et al., 2014 carried out sensitivity analysis using global methods. Their results show that CN2 is the most sensitive parameter for purposes of calibration. A review by Arnold et al., 2012 concluded that CN2 was the parameter which was mostly used for calibration of surface runoff. CN2 is dependent on land use cover, antecedent soil water conditions and soil permeability. Other sensitive parameters from Table 4.2 are ESCO, Gwqmn SOL-AWC, ALPHA-BF and Revapmn. These parameters are also commonly used by other researchers (Arnold et al, 2012; Manoj, 2009) From Table 4.2, the bottom 13 parameters were ignored during calibration as any modification did not result in any significant change in the simulated discharge values.

4.2.3 Calibration/ Validation Parameter Values and Model Performance

The Table 4.3 shows the results of the calibration which was guided by the results of the sensitivity analysis. The selected parameters were also compared to the choice of parameters which were used by other researchers who used SWAT in the same study area or surrounding regions (Kigira 2007; Nkonge et al., 2014). Kigira used the parameters recommended in Neitsch et al (2002b). These parameters include CN2, SOL-AWC, GW-REVAPMN and GWQMN.

Table 4.3 Calibrated Values

Parameter	**Rank**	Parameter description	Calibrated value
Cn2	1	Initial SCS CN II value	Forests: 42.7-57 Agriculture: 73.1-79 Shrub: 58.95 Urban: 81.22 Coffee: 62.7-78 Tea: 79
Esco	2	Soil evaporation compensation factor	Replaced by 0.96
Gwqmn	3	Threshold depth of water in the shallow aquifer required for return flow to occur	Replaced by 20mm
Revapmn	4	Threshold water in the shallow aquifer for revap to occur	Replaced by 100mm
Sol_Z	5	Soil depth	800-1020 mm
Sol_Awc	6	Available water capacity	40 – 126mm
Alpha_Bf	7	Base flow alpha factor	Replaced by 0.0396
LAI		Leaf Area Index	Forest LAI replaced by 6

Selected parameters were varied and adjusted with the aim of getting the best fit between observed and simulated values as per the statistical indices NSE and R^2. The surface runoff was calibrated first by adjusting CN2, ESCO and SOL-AWC, followed by the base flow which was calibrated by adjusting gwqmn, revapmn and alpha-bf and the results are as shown in Table 4.4 below.

Table 4.4 Average Annual observed and simulated flows RGS 4CA02

	Total Water Yield	**Base flow**	**Surface Flow**
Actual	21.28m3/s	17.02m3/s	4.26m3/s
SWAT	21.18m3/s	17.03m^3/s	4.15m^3/s

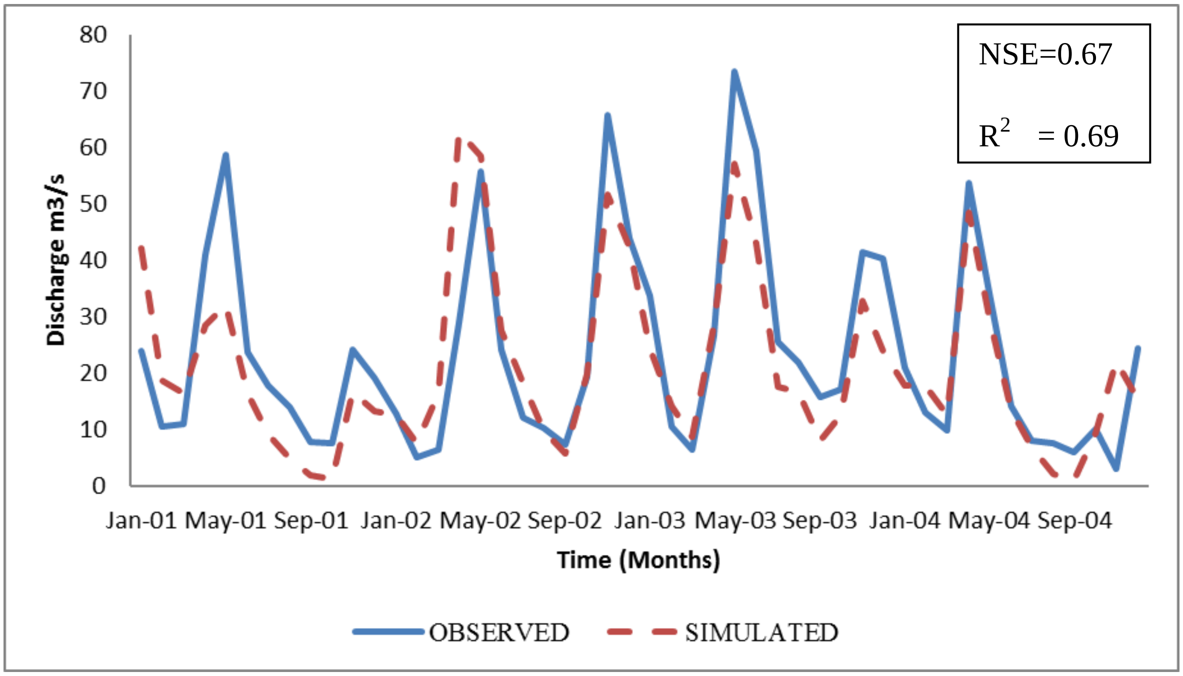

Figure 4.2 Calibration results for RGS 4CA02

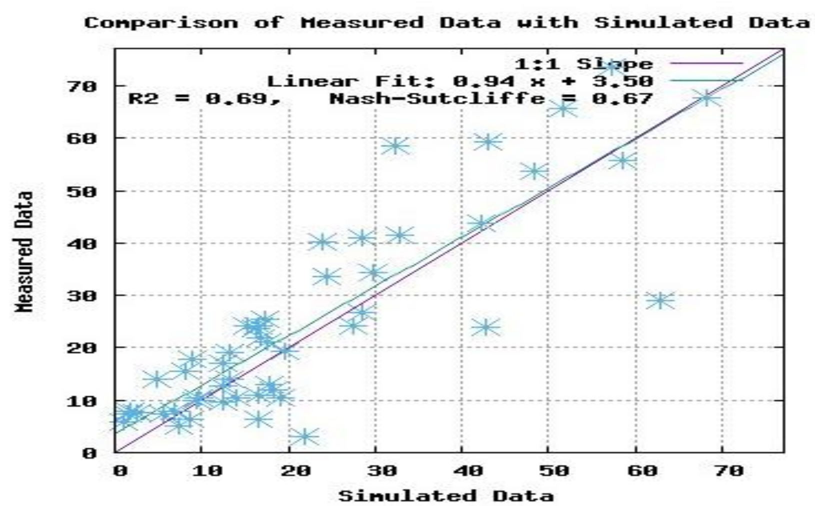

Figure 4.3 Comparison of measured data with simulated data for calibration period using scatter gram

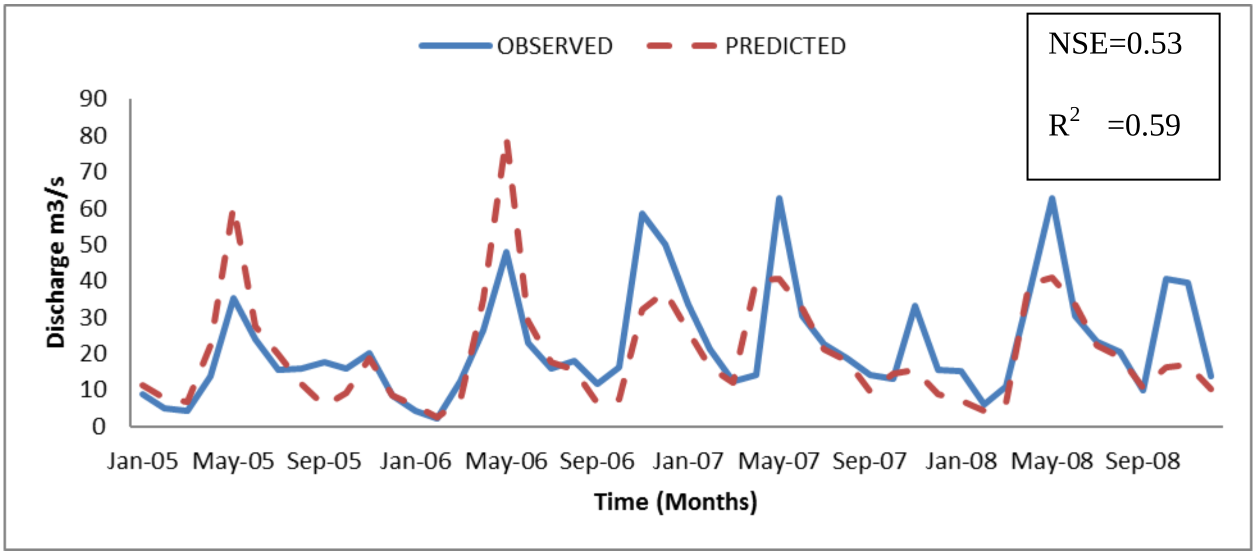

Figure 4.4 Validation results for RGS 4CA02

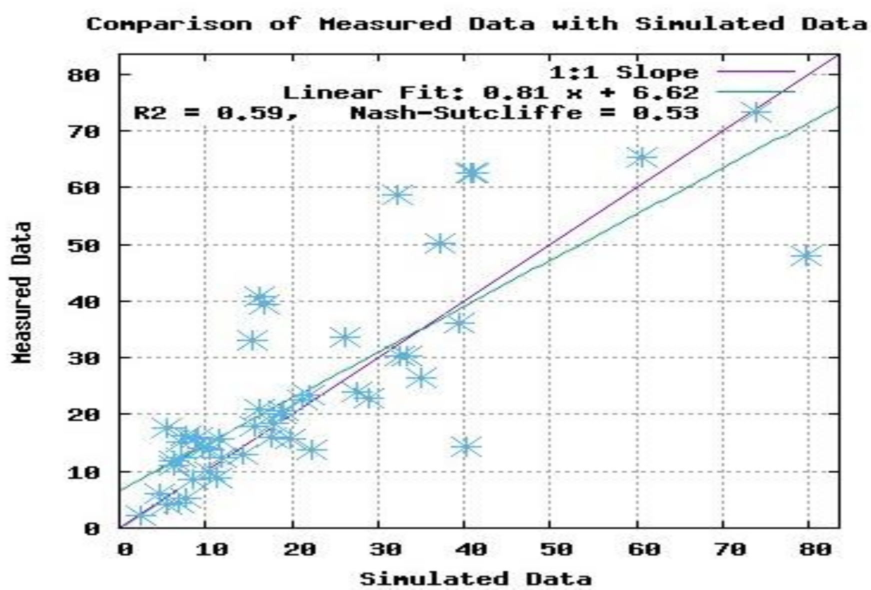

Figure 4.5 Comparison of measured data with simulated data for validation using scatter gram

Figures 4.2 and 4.4 show the graphical representation of calibration and validation results respectively while Figure 4.3 and 4.5 show the linear relationship between the observed and simulated data. The results and the performance rating are shown in Table 4.5.

Table 4.5 Calibration and Validation results

	Calibration	Performance Rating	Validation	Performance Rating
NSE	0.67	good	0.53	satisfactory
R^2	0.69	good	0.59	satisfactory
PBIAS	8.87	Very good	12.24	good

NSE, R^2 and PBIAS values obtained for the calibration period were 0.67 and 0.69 and 8.87 respectively. According to Moriasi et al., (2007), this means that the performance of the model in simulating stream flow was good and very good. These results are in close agreement with the results gotten by Kigira, (2007). The author calibrated the SWAT model using data from a RGS in Thika river and got an NSE value of 0.68. Validation results for this research gave NSE, R^2 and PBIAS values of 0.53, 0.59 and 12.24 respectively. This means that the performance of the model for validation was satisfactory. According to PBIAS, the performance was good. The model, however, failed to simulate some peak flows. Similar underestimations have also been observed by other researchers (Qiu et al.,2012; Van Liew et al.,2007). This can be attributed to input data and model uncertainties. The model performed better in calibration than in validation. Similar results were also gotten by Tetsoane, (2013) and Panagopoulos et al.(2015).

4.3 Temporal Dynamics of Parameter Sensitivity

For the 8 SWAT parameters which were chosen to represent hydrological processes, 243 model runs were required. The 243 parameter sets which were generated by FAST are detailed in Appendix 1. The output from all 243 runs were again applied to FAST to generate the temporal sensitivities and the results were as follows.

4.3.1 Runoff Processes

The results of TEDPAS for CN2 and surlag showed that the temporal sensitivities of the two runoff parameters varied with time. These sensitivities were compared with the stream flow hydrograph from RGS 4CA02. Stream flow was generally divided into four parts; peak flows, recession, low flow and re saturation periods. Figure 4.6 shows a comparison of temporal sensitivity of CN2 and surlag with stream flow.

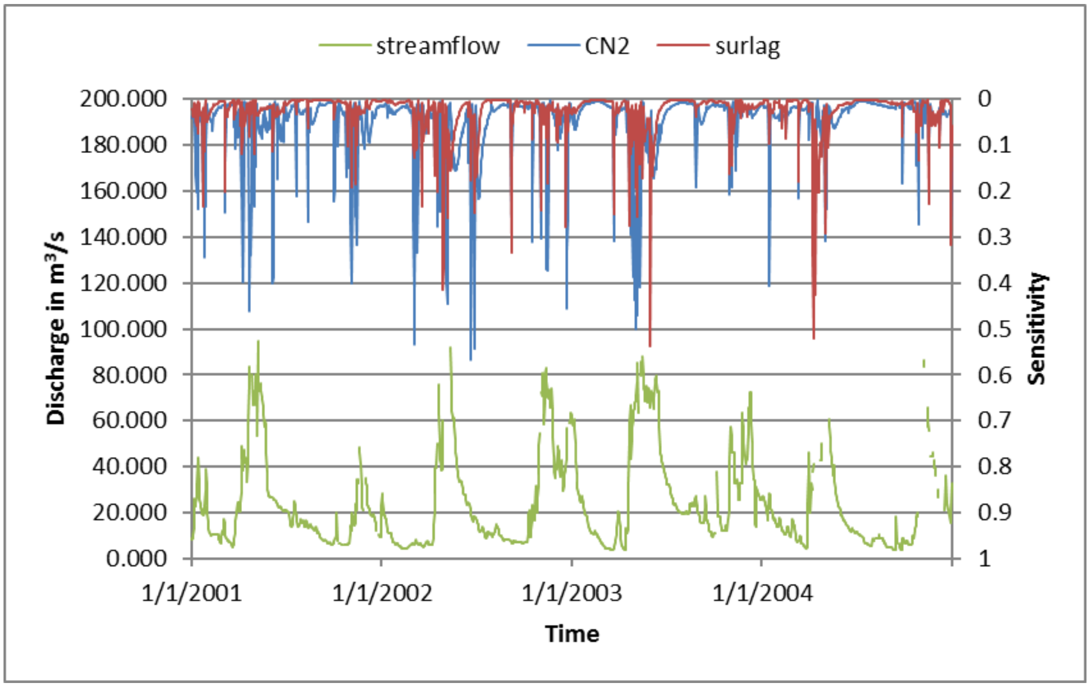

Figure 4.6 Comparison of temporal sensitivity of CN2 and surlag with streamflow

The primary horizontal axis shows the variation of stream flow with time from the year 2001 to 2004. The secondary horizontal axis shows the temporal variation of sensitivity of CN2 and surlag over the same period. Sensitivity of CN2 varied from a low of 0 to a high of 0.57, while the sensitivity of surlag varied form a low of 0 to a high of 0.52. These two parameters are sensitive for short durations. When compared to stream flow, high values as mostly noted during peak flows while the lowest value of sensitivity are noted during low flows. Due to the close relationship between runoff and precipitation, the temporal sensitivities of CN2 and surlag were also compared to precipitation as shown in Figure 4.7. Increased sensitivity was mostly noted during or immediately after rainfall events. This is also because CN2 is dependent on rainfall and moisture conditions of the soil. Whereas CN2 controls the magnitude of surface runoff, SURLAG controls its timing in contributing to stream flow. These parameters are sensitive for short periods, especially during precipitation events because runoff processes are faster compared to groundwater processes. These results indicate that runoff processes are most active in generating stream flow during peak flow seasons which are mostly characterized by rainfall events. These results were compared with the results gotten by (Guse et al, 2016; Guse et al, 2013). Their results for an upland catchment show that CN2 was rarely dominant and had high sensitivity for short periods. Surlag was also sensitive in the same periods.

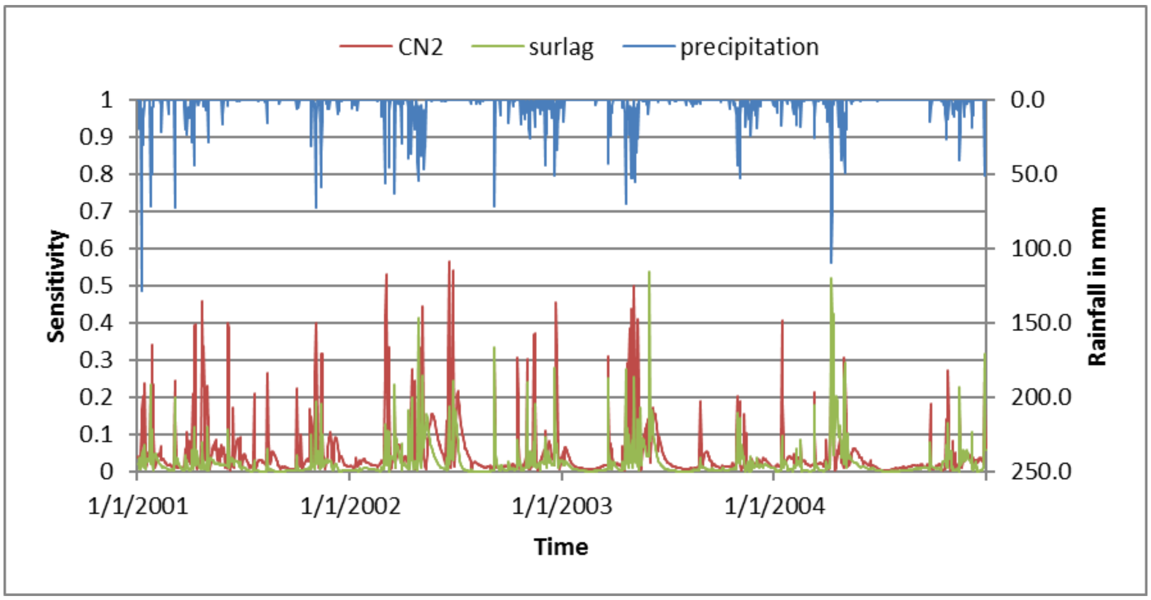

Figure 4.7 Comparison of rainfall with temporal sensitivity of CN2 and surlag.

4.3.2 Evapotranspiration process

Canmax and Esco are dominant at different periods as shown in Figure 4.8. Both Canmax and ESCO varied from a low of 0 to highs of 0.53 and 0.45 respectively. When compared to stream flow as shown in Figure 4.8, canmax has high peaks mostly during resaturation periods as the stream flow is transitioning from low flows. The lowest sensitivities are seen during low flows. The results of the temporal sensitivity of ESCO show an antagonistic nature against CANMAX. Where peaks in Canmax sensitivity are noted, sensitivity of ESCO records a low value and vice versa. High sensitivities of

ESCO are seen during peak flows and re saturation periods. Water intercepted and stored by canopies is from precipitation. This water is then lost through evaporation. These results mean that only when the canopy storage is empty is the soil water used for evaporation. This explains their antagonistic nature. Guse et al.(2013) found that ESCO demonstrated high sensitivities when the soil became wet after long dry periods. These periods corresponded to resaturation periods.

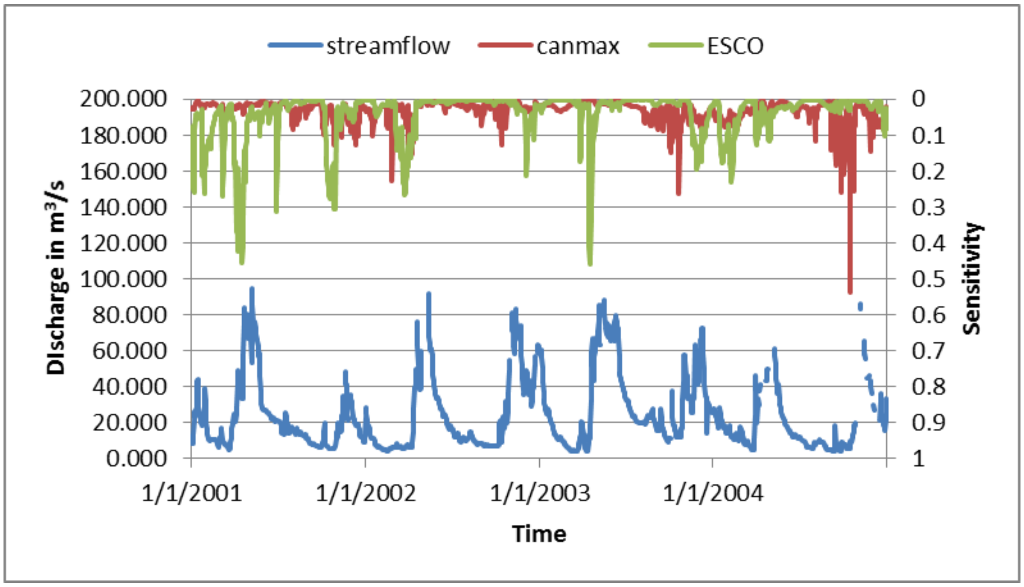

Figure 4.8 Comparison of streamflow with the temporal sensitivity of canmax and ESCO

4.3.3 Groundwater processes

Groundwater parameters are sensitive for longer time periods as shown in figure 4.9 and 4.10 compared to the runoff and evaporation parameters. For all three ground water parameters, the lowest value of sensitivity is 0. The highest value of sensitivity for gw-delay, alpha-bf and rchrg-dp were 0.33, 0.35 and 0.42 respectively. High sensitivities of the three ground water parameters are recorded during low flows, peak flows and recession periods. These results mean that ground water processes are dominant in those three phases of the streamflow. Guse et al, (2016) found that the three groundwater parameters are sensitive during peak and recession phases.

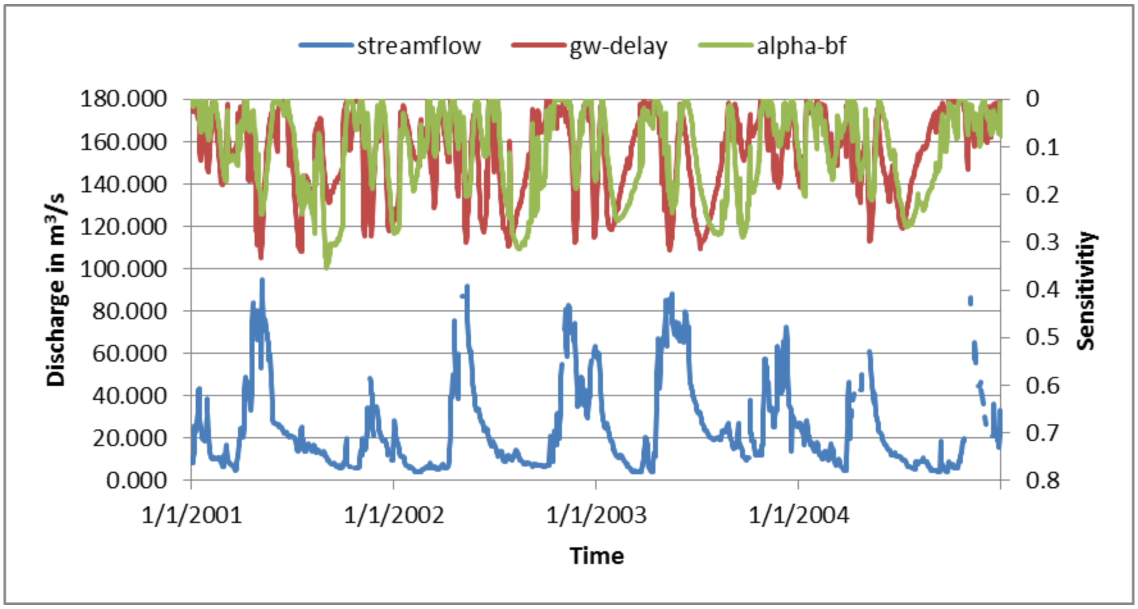

Figure 4.9 Comparison of stream flow with temporal sensitivity of Gw-delay and Alpha-bf

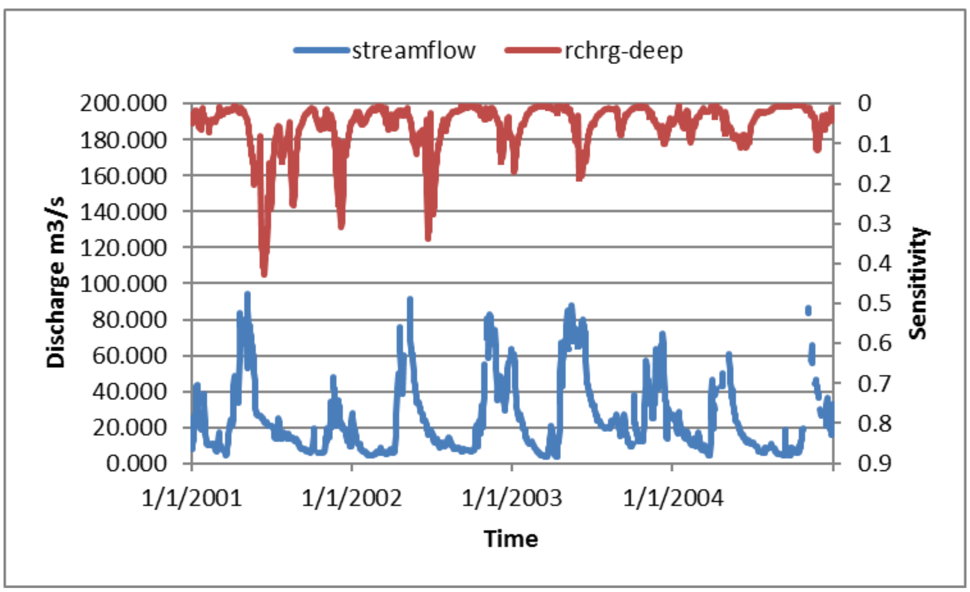

Figure 4.10 Comparison of stream flow with temporal sensitivity of rchrg-dp

4.3.4 Soil Processes

SOL_AWC has periods of dominance and also periods of low sensitivity. When compared to the stream flow shown in figure 4.11, periods of high sensitivity are mostly detected during re saturation and peak flows. The lowest sensitivity is 0 while the highest is 0.69. This parameter records the highest sensitivity and longer durations of detected sensitivity compared to all other parameters. This means that the corresponding process, soil processes, are highly influential in stream flow variability. These results are comparable to results gotten by Guse et al, 2016. SOL-AWC parameters had medium to high sensitivity most of the day.

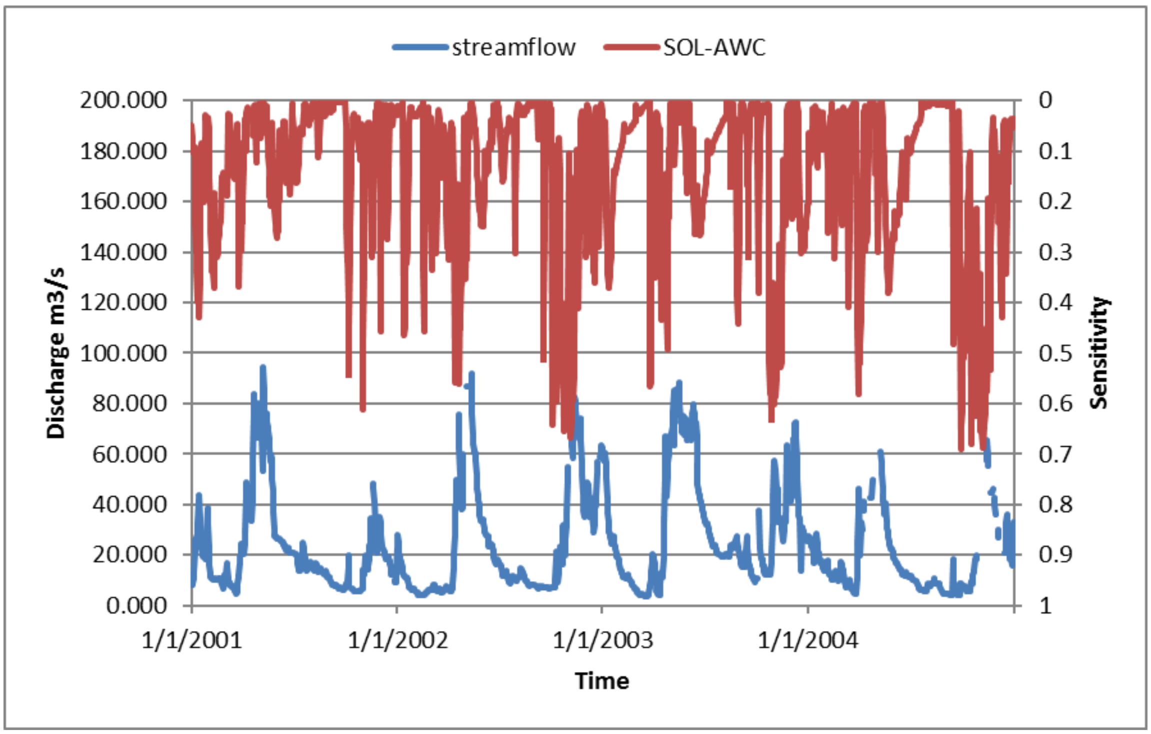

Figure 4.11 Comparison of stream flow with temporal sensitivity of SOL-AWC

4.3.5 Comparison of Flow Duration Curve (FDC) to Sensitivities

In order to determine whether the detected high sensitivities of a parameter can be related to certain discharge magnitudes, a FDC shown in Figure 4.12 was used as done by Guse et al.(2016). The FDC was divided into five segments using the flow exceedance probability at the 5%, 20%,70% and 95% points as boundaries. The sensitivities for each segment of the FDC is shown in Figure 4.13. The values 1-12 represent the months of a year. For the first segment of the FDC curve,Q0-Q5, the lowest sensitivities are seen for canmx and ESCO. CN2, Surlag, Rchrg_dp, Gw-delay and alpha-bf are relatively sensitive. The highest sensitivity is detected for SOL-AWC. For Q5-20 the lowest sensitivities are seen for Canmx.

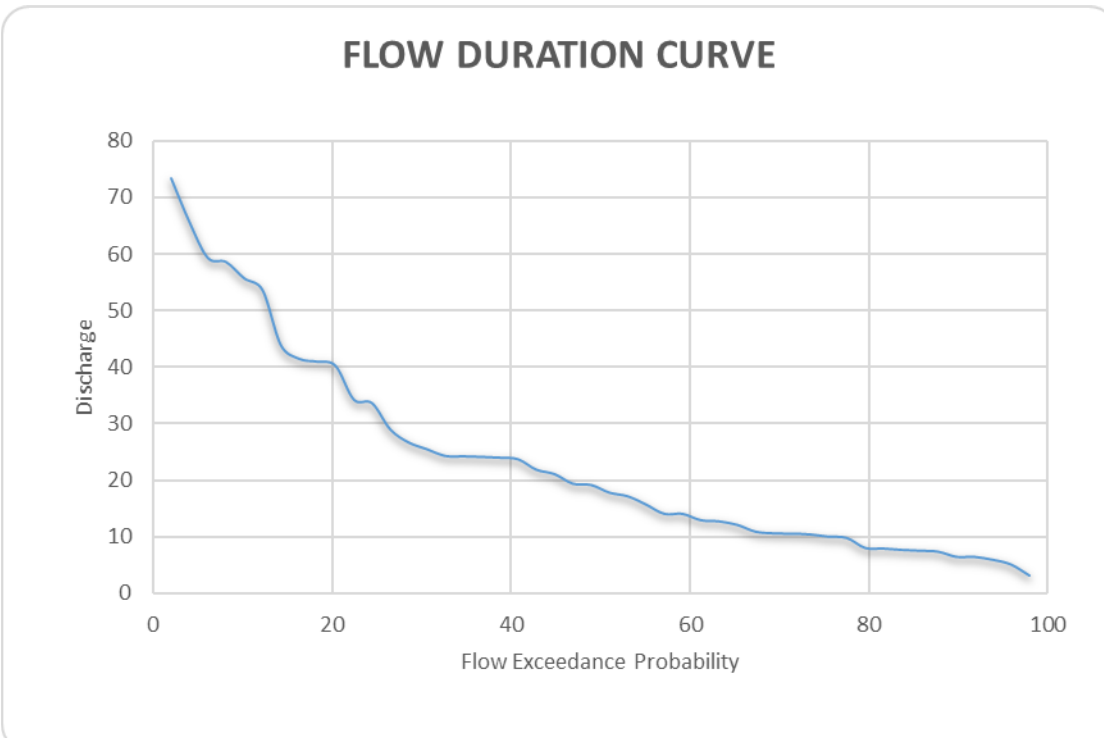

Figure 4.12 Flow duration curve

All other parameters are relatively sensitive with the highest sensitivity being detected for SOL-AWC. For Q20-70, the lowest sensitivities are detected for CN2, surlag, canmx and ESCO. All the other parameters are more sensitive with the highest sensitivity occurring for SOL-AWC. For Q70-95 the least sensitive parameters are Surlag, CN2, Rchrg deep and Canmx. Gw-delay, alpha-bf and SOL-AWC are most sensitive. For the low flow, Q95-100, SOL-AWC is most sensitive followed by alpha-bf and gw-delay.

Rchrg-deep, CN2, surlag canmx and Esco are least sensitive for this flow regime. These runoff parameters are relatively sensitive during high magnitudes of stream flow. No sensitivity is detected during low flow conditions. The occurrence of surface runoff increases in periods with high-precipitation and high-soil-moisture conditions as per the curve number method. SURLAG is sensitive also in the same phases. This means that runoff processes are insignificant during low flows. The sensitivities of ground water parameters are detected in all five segments of the FDC. The highest sensitivities are detected in Q70-Q95 and Q95-Q100 segments.

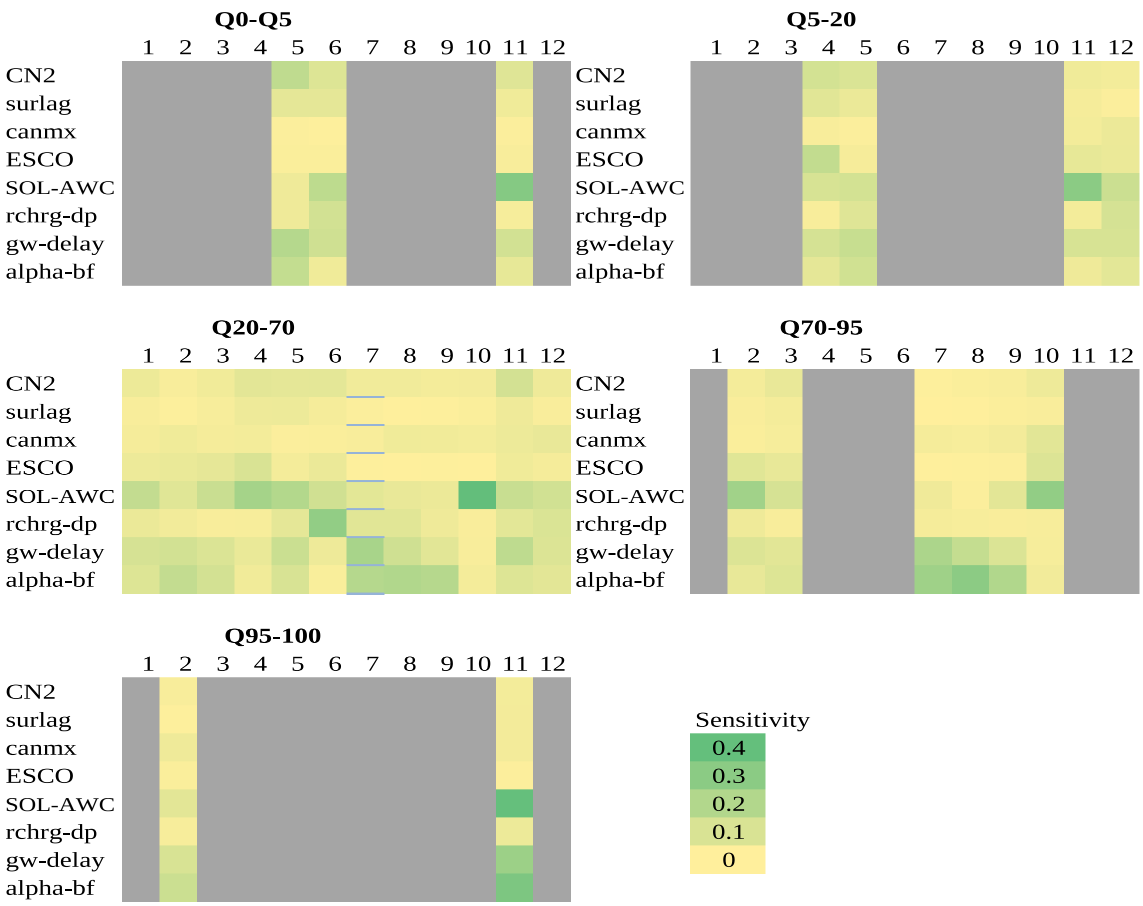

Figure 4.13 Sensitivity of parameters at different flow magnitudes.

Rchrg _dp is not as sensitive as the other ground water parameters during low flows .The sensitivity of RCHRG_DP increases directly with increasing discharge. RCHRG_DP is the fraction of the recharge from the soil to groundwater that is lost into the deep aquifer, and thus, its effect on the groundwater flow increases with increasing recharge values (Neitsch et al., 2011). RCHRG_DP has some periods of high sensitivity in the Q20-Q70 segment of the FDC. SOL-AWC is sensitive in all five segments of the FDC. This pattern is detected because SOL-AWC also controls occurrence of surface and lateral flows. It also controls how water percolates into ground water. These results mean that low flows are characterized by soil and groundwater processes. These results are comparable to Guse et al., 2016. The authors concluded that CN2 was relatively sensitive during medium to high flows. Ground water parameters were sensitive during both high and low discharges.

4.4 Spatio-Temporal Variability of water balance components

The water balance components of the Chania catchment varied both in space and time. Figures 4-14 to 4-19 show the spatial variation of the different water balance components.

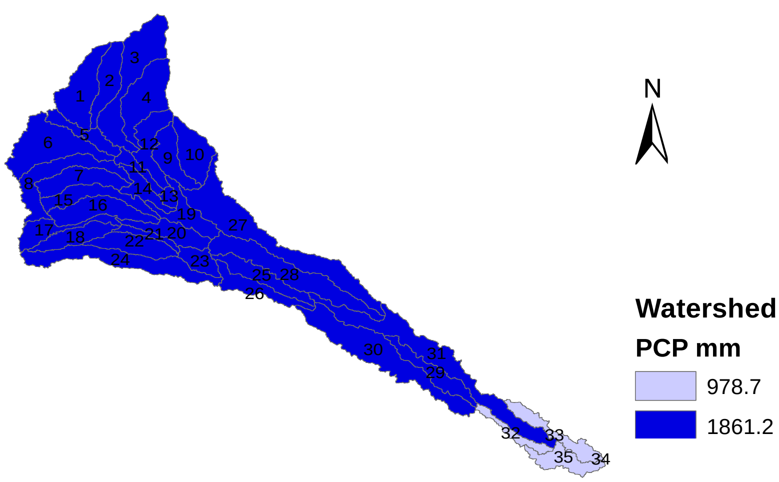

Figure 4.14 Annual average spatial variability of Rainfall in Chania catchment

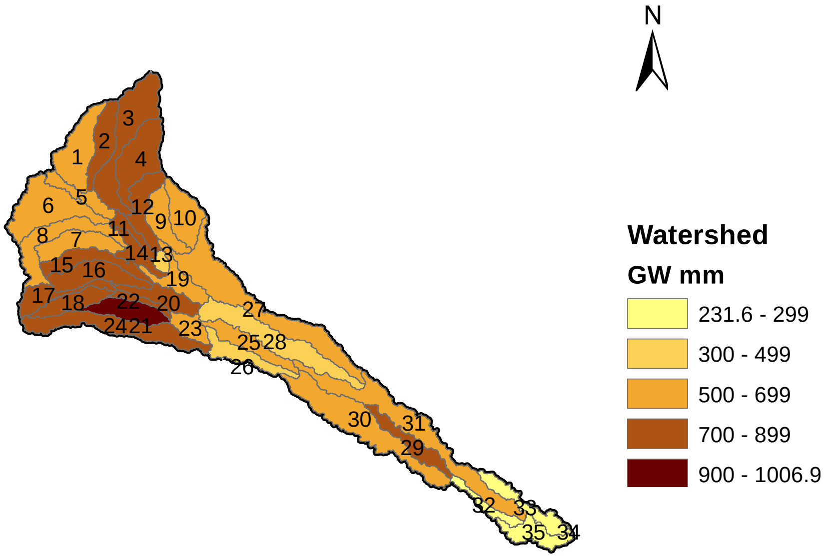

Figure 4.15 Annual average spatial variability of Ground Water in Chania catchment

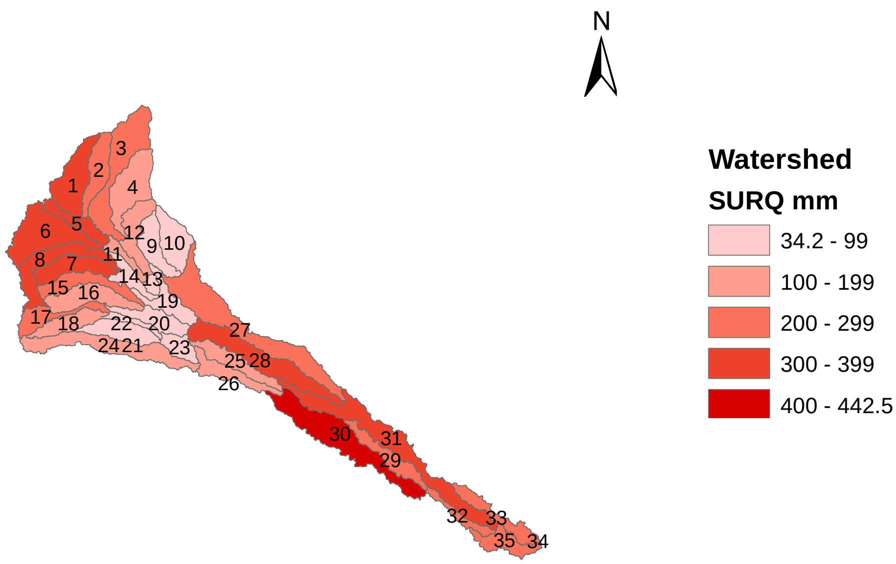

Figure 4.16 Annual average spatial variability of Surface Runoff in Chania catchment

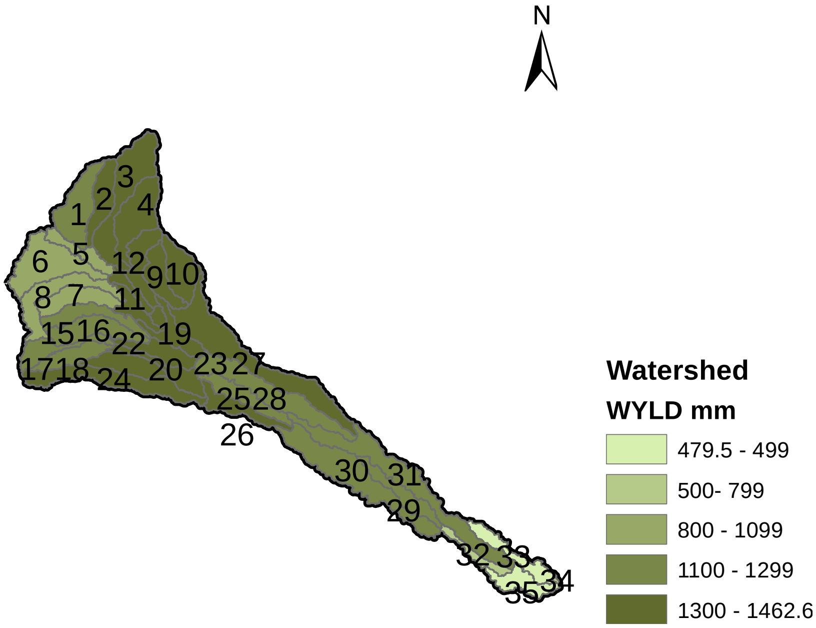

Figure 4.17 Annual average spatial variability of Water Yield in Chania catchment

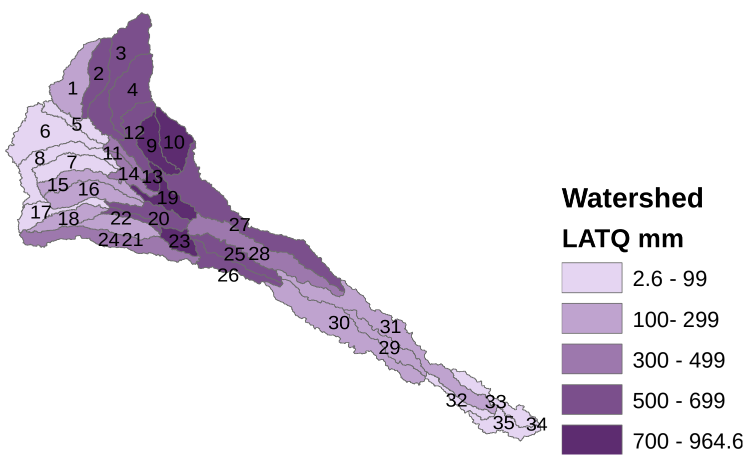

Figure 4.18 Annual average spatial variability of Lateral Flow in Chania catchment

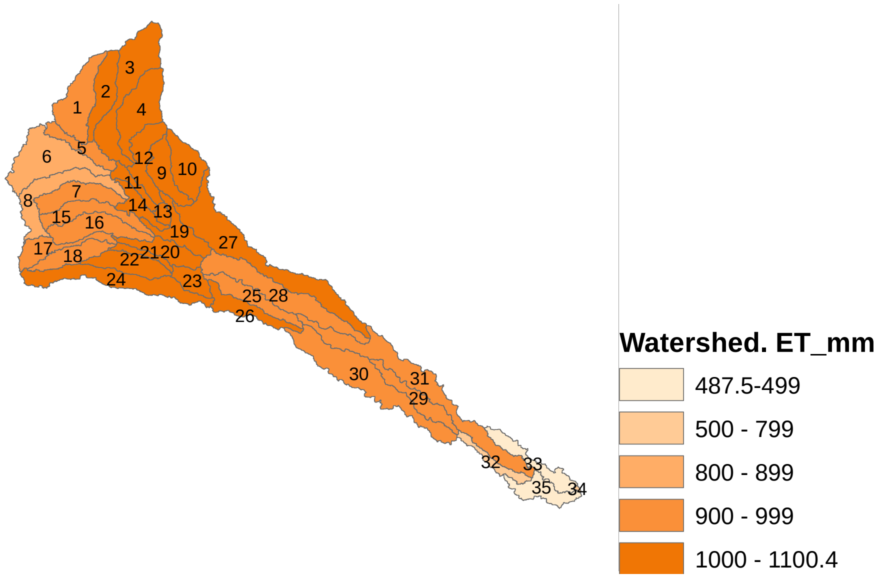

Figure 4.19 Annual average spatial variability of Evapotranspiration in Chania catchment

Figure 4.14 shows the spatial distribution of average rainfall over the Chania watershed. Subbasins located in higher altitudes receive more rainfall compared to lower altitude subbasins located near the basin outlet. Annual average rainfall varied spatially from 1861.2 mm to 978.7 mm. Ground water varied spatially across the subbasins from a high of 1006.9 mm to a low of 231.6mm as shown in Figure 4.15. The highest amounts of ground water were noted in basins located towards the North-West side of the watershed. These regions are characterized with loam, silty loam, sandy clay loam and clay soils. Land cover in the subbasin 22, which had the highest amount of groundwater, was 73% forest and 27% shrub. Subbasin 35 had the least amount of groundwater. Land cover in this subbasin was 50% coffee, 27% agriculture, 19% wetland and 4% shrub. Annual average surface runoff varied spatially as shown in Figure 4.16. The amount of surface runoff varied from 442.5 mm to 34.2 mm. Subbasin 30 had the highest amount of runoff. This subbasin had 67% Agriculture, 15% Shrub and 17% Tea. The least amount of surface runoff was generated by subbasin 9. This subbasin consists of 94% forest cover and 6% shrub. The pattern of the spatial variation of surface runoff was opposite to that of ground water. This means that subbasins with high surface runoff values had lower ground water values and vice versa. Regions with high runoff were characterized by andohumic nitisols, humic nitisols, eutric planosols and haplic phaozems. The textures of these soils were silty loam and clay. Average annual water yield varied from 1462.6 mm to 479.5 mm. High amounts of water yield are noted in the northern parts of the watershed while the least amounts are noted on the south east parts of the watershed as shown in Figure 4.17. Subbasin 13 had the highest amount of water yield with the present land cover being 100% forest cover. Subbasin 35 had the least amount of water yield. Land cover in this subbasin consisted of 50% coffee, 27% agriculture, 19% wetland and 4% shrub. Annual average lateral flow varied spatially as shown in Figure 4.18. Values ranged from 964.6 mm to 2.6 mm. Subbasin 13 had the highest amount of lateral flow while subbasin 33 had the least amount of lateral flow. Land cover in subbasin 33 was 73% Coffee and 27% wetland. Areas which demonstrated high values of lateral flow were mainly of loam soil and sandy clay loam texture. Annual average values of ET varied spatially across the subbasins as shown in Figure 4.19. The highest value, resulting from subbasin 19, was 1100.4 mm while the lowest value, recorded in subbasin 33, was 487mm. The land cover in subbasin 19 was 100% forest.

Generally, the subbasins where the highest values of water balance components were noted were located in regions which received high amounts of rainfall. Low values of water balance components were detected in subbasins which received low rainfall. There was also variation of water balance components in subbasins which received the same amount of rainfall. This can be attributed to the different land covers and soil types in the sub basins. Lateral flow and ground water flow were high in subbasins which had silty loam and loam soil. High amounts of surface runoff noted in the upper part of the catchment are attributed to the low drainage properties of planosols (Mwangi et al., 2015). These results mean that the spatial variability of water balance component in Chania catchment are dependent on rainfall, land cover and soil properties. These results are comparable to results gotten by other researchers (Kigira, 2007 ; Yin et al., 2016)

Kigira used SWAT model to determine the spatial variability of surface runoff in Thika catchment for the year 1984. Chania catchment is located within Thika catchment. The author's results show a similar trend with this study with areas near subbasin 30 (in this study) having high amounts of runoff. Other slight variations in runoff can be attributed to the difference in land use map and simulation period used. Yin et al., (2016) indicated that all water balance components varied spatially. Their results show that quantities of groundwater and surface runoff were antagonistic across the sub-watersheds in their area of study. Figure 4.20 and 4.21 shows the annual temporal variability of water balance components. The average annual precipitation varied from 2376.57 mm to 1499.03 mm. The highest precipitation is noted in the year 2002. Surface runoff ranged from 344.03 mm to 129.22mm with the highest value being recorded during the highest precipitation events. Ground water values range from 503.66 mm to 765 mm. Lateral flow values ranged from 291.40mm to 510.5mm while ET ranged from 670.4mm mm to 850mm.

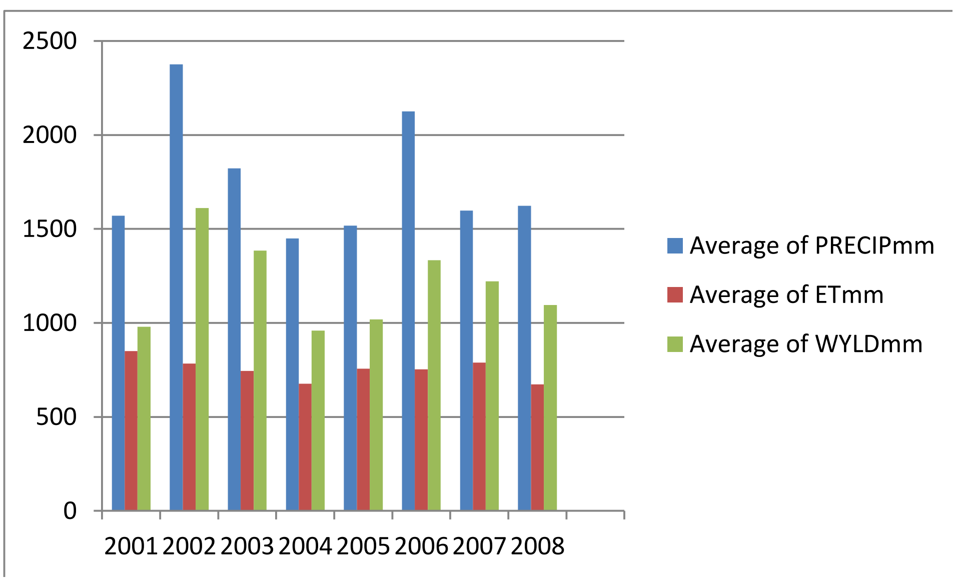

Figure 4.20 Annual Temporal Variability of precipitation, ET and Water Yield

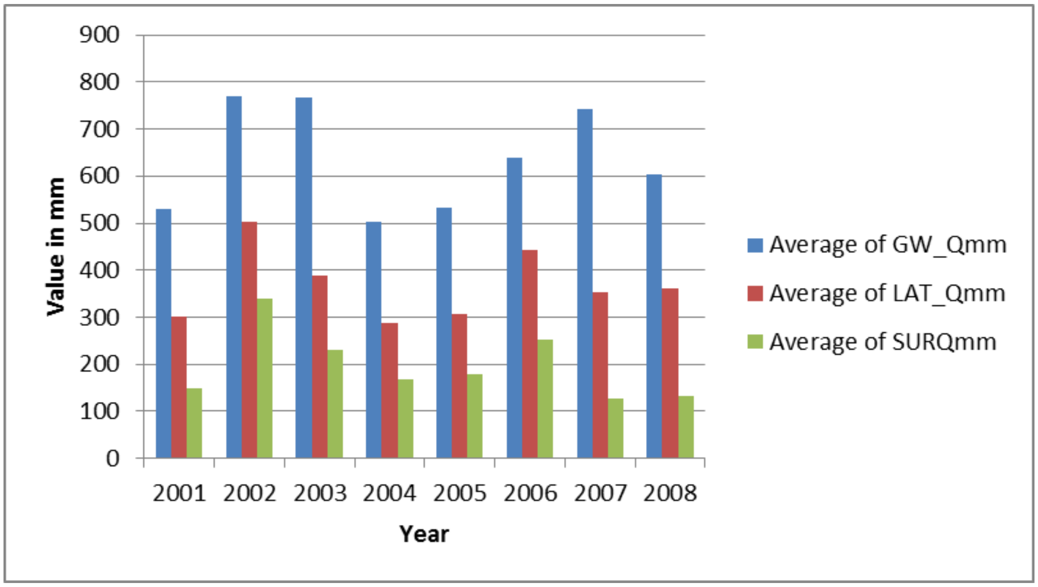

Figure 4.21 Temporal Variability of surface runoff, ground water and lateral flow

Most of the rainfall received in the catchment water is converted to ground water. Figure 4.22 to Figure 4.27 shows how the individual water balance components vary seasonally.

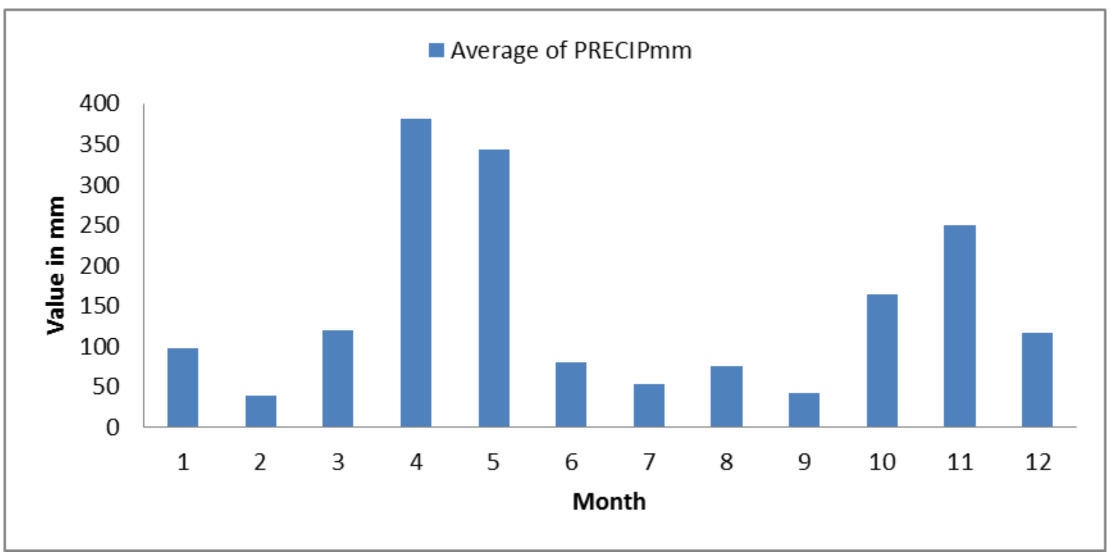

Figure 4.22 Seasonal variability of precipitation

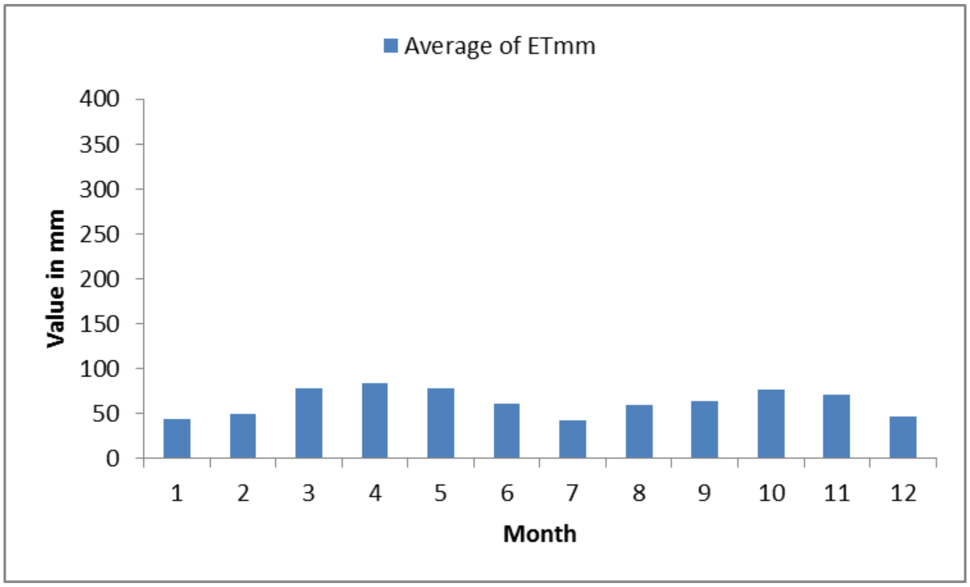

Figure 4.23 Seasonal variability of evapotranspiration

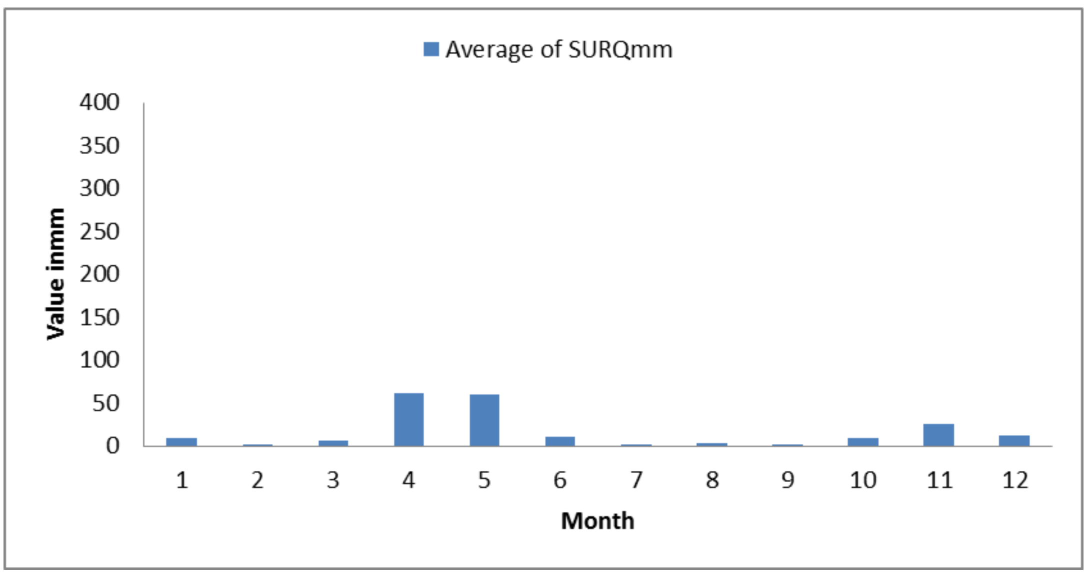

Figure 4.24 Seasonal variability of surface runoff

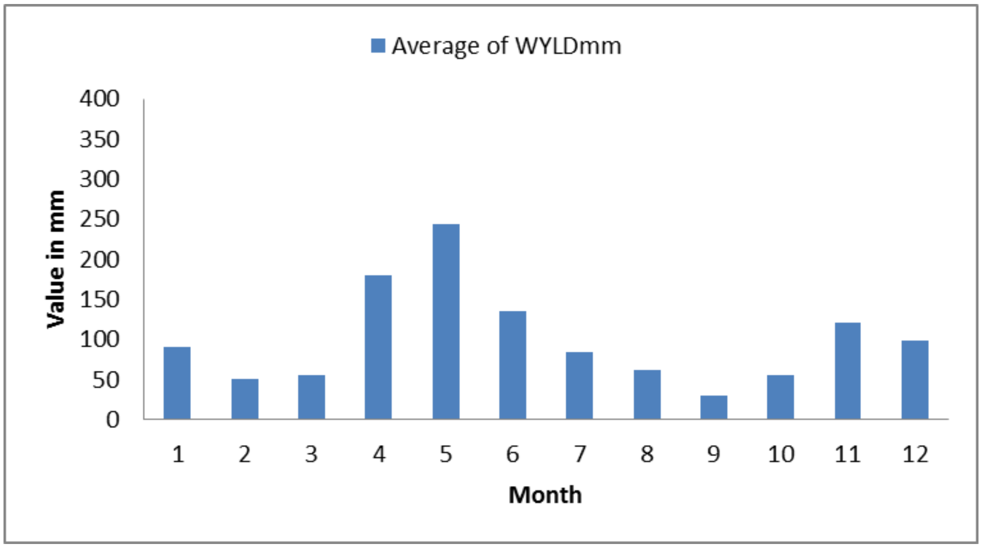

Figure 4.25 Seasonal variability of water yield

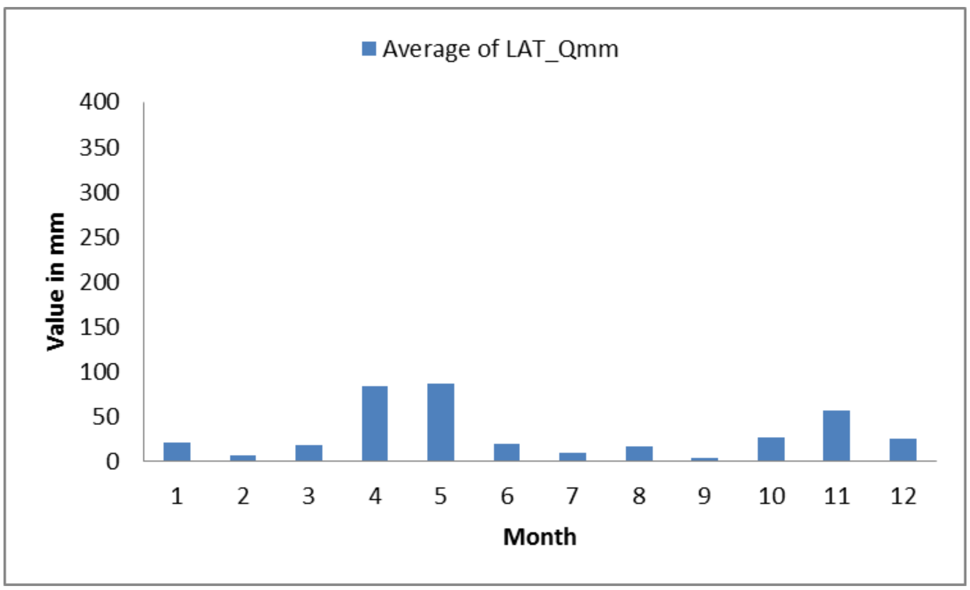

Figure 4.26 Seasonal variability of lateral flow

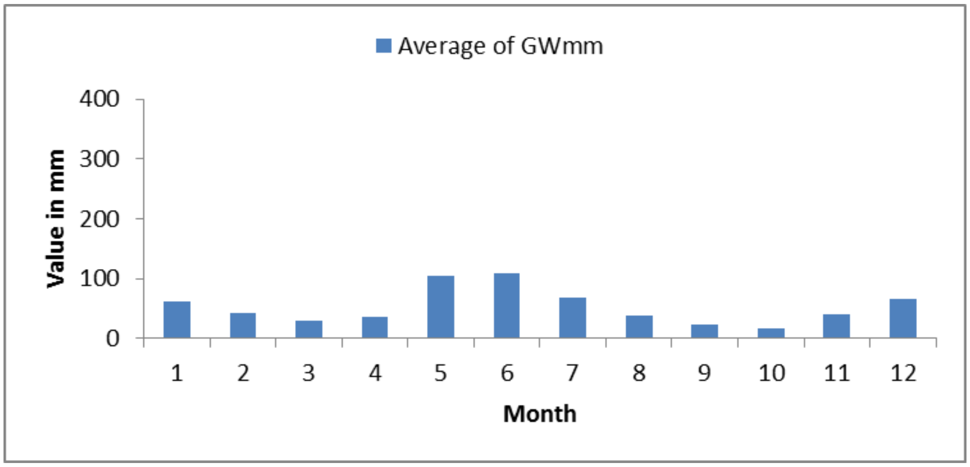

Figure 4.27 Seasonal Variability of Ground water

The figures represented on the graphs in Figure 4.22 to Figure 4.27 are the respective monthly averages. Precipitation varied seasonally with peaks seen in the months of April-May during the long rains and October-December during short rain season. The seasonal variation of runoff, ET, lateral flow and water yield tend to follow the variation of precipitation with peaks witnessed in the same periods. This means that hydrologic processes in the Chania catchment are influenced by rainfall. Ground water tends to have a lag in its seasonal variation compared to the other water balance components. This is because ground water processes are slow compared to the other hydrological processes. Evaporation is usually the process through which catchments lose water. Because precipitation always exceeds evaporation, it can be concluded that Chania catchment acts as a sink for moisture. These results are comparable to results gotten by Manashi, 2016. The author found that the seasonal variability of surface runoff and ET followed the variations in precipitation. Marengo (2004) assessed the temporal variability of water balance and found that precipitation exceeded evaporation. Instances when evaporation exceeded precipitation were associated with extreme events such as La nina.

4.5 Effect of land cover change on water balance components

Simulations under all scenarios indicated changes in all water balance components. In scenario I, all forest cover was converted to agricultural land. Simulation under Scenario I indicated a reduction of 6.44% in groundwater, 3.52% in water yield and 6.83% in lateral flow and 3.39 in ET. Surface runoff increased by 12.93%.

In scenario II, 50% of forest land was converted to agricultural land. Simulations under this scenario indicated a reduction of 3.27% in groundwater, 1.76% in WYLD and 3.14% in lateral flow and 1.62% in ET. Surface runoff increased by 6.31% .

In scenario III, 50% of forest cover was converted to shrub land. The results show a reduction of 2.39% in ground water, 2.46% in water yield and 3.06% in lateral flow and 1.02% in ET. Surface runoff increased by 3.83%.

In scenario IV, all shrub land was converted to urban area. The results show a reduction of 0.15% in groundwater, 0.24% in ET and 0.04% in lateral flow. Surface runoff and water yield increased by 1.15% and 0.11% respectively.

In scenario V, Shrub land and agricultural land were each reduced by 25 % in favour of forest cover. Results indicated an increase of 0.61%, 0.44%, 1.07% and 0.2% in groundwater, water yield, ET and lateral flow respectively. Surface runoff reduced by 0.43%. The summary of the effects of the five scenarios on the water balance is summarized in Table 4.6. Table 4.7 shows values of Mean, maximum and minimum stream flow for the baseline and simulated scenarios.

Table 4.6 Effects of different land use scenarios on the water balance

	GW	WYLD	LATQ	ET	SURQ
Scenario I-CDA	-6.44%	-3.52%	-6.83%	-3.39%	+12.93%
Scenario II-PDA	-3.27%	-1.76%	-3.41%	-1.62%	+6.31%
Scenario III PDS	-2.39%	-2.46%	-3.06%	-1.02%	+3.83%
Scenario IV-Urbanization	-0.15%	+0.11%	-0.04%	-0.24%	+1.15%
Scenario-V afforestation	+0.61%	+0.44%	+0.20%	+1.07%	-0.43%

Table 4.7 Mean, maximum and minimum stream flow for the baseline and simulated scenarios

	Mean stream flow	**Maximum stream flow m³/s**	**Minimum stream flow m³/s**
Baseline conditions	20.71	79.53	1.08
Scenario I-CDA	19.90	79.61	1.04
Scenario II-PDA	20.31	79.57	1.06
Scenario III PDS	20.15	78.55	1.05
Scenario IV-Urbanization	20.71	79.58	1.08
Scenario-V afforestation	20.78	79.52	1.09

From Table 4.6, all scenarios apart from afforestation lead to a reduction in ground water and lateral flow contribution to stream flow. Afforestation retards runoff allowing water to infiltrate and contribute to ground water. All scenarios which involved reduction of forest cover led to a decrease in water yield. Scenario II resulted in more runoff than scenario III. This can be attributed to shrubs having denser canopy cover than agriculture. This in turn intercepts rainfall and retards runoff. Reduced water yield as a result of deforestation can be attributed to the reduction in ground water and lateral flow. Deforestation and urbanization both lead to an increase in runoff. Reduced ground water due to deforestation and urbanization mean that the low flows are reduced. From Table 4.7, deforestation reduces the mean and minimum stream flow while increasing the maximum flow. Urbanization on the other hand increased peak flows but had no notable effect on the mean and minimum flow. In addition to that, scenario I, II and III had greater impacts on the water balance compared to scenario IV. This can be attributed to the fact that the scenario of urbanization was only applied to three subbasins leading to minimal or insignificant effect at the entire watershed level. These results mean that any further deforestation in Chania catchment will result in decreased base flow and increased quick flow. This will lead to a decrease in water availability especially during low flow seasons thereby exacerbating water scarcity. These results are comparable to results gotten by other researchers who investigated effects of land use changes on the hydrology of other catchments. Mango et al., 2010 indicate that all conversions of forest cover to agriculture led to reduced base flow. On the contrary, Bithell and Brasington (2009) found that reducing forests led to an increase in evaporation and internal soil storage and a reduction in annual discharge. Zhang et al., 2001 as reported by Geertsma et al., (2009) suggests that converting forests to agriculture or bare land could lead to increased evaporation. Ya et al., (2012) indicate that urbanization leads to increased peak flow in river discharges.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Brief on the chapter

This chapter consists of a summary of the research conducted in section 5.1. Section 5.2 contains the conclusions arrived at based on the results. The final section, section 5.3 contains recommendations based on the study in general.

5.2 Summary

The objective of this research was to model hydrological processes in the Chania river system. Four specific objectives were formulated in order to achieve this goal. These were; to develop the SWAT model for use in Chania catchment, to determine hydrological processes that govern the temporal variability of stream flow, to determine the spatio-temporal variability of water balance components and to determine the effects of land cover changes on the water balance and the hydrology of the catchment.

Before the model was calibrated, sensitivity analysis and base flow separation were performed. Sensitivity analysis was conducted using a combination of LH and OAT methods in order to identify the model parameters to be adjusted during calibration. Base flow separation was done on the total stream flow using a base flow filter in order to separate base flow from surface flow for a more efficient calibration process. The model was calibrated manually at a monthly time step by adjusting the parameters until a reasonable fit between observed and simulated values of stream flow was achieved. Calibration and validation were done using stream flow data for the years 2001-2004 and 2005-2008 respectively. To assess the goodness of fit NSE, R^2 and PBIAS were used as indicators.

In order to determine the hydrological processes that govern the temporal variability of stream flow, TEDPAS was applied to the SWAT model. This was done using FAST in the R programming language. Eight model parameters representing different processes were selected. CN2 and Surlag represented runoff processes, ESCO and CANMAX represented evaporation processes, rchrg-dp, gw-delay and alpha-bf represented ground water processes while SOL-AWC represented soil processes. In order to determine whether the detected high sensitivities of a parameter can be related to certain discharge magnitudes, a FDC was used.

Upon successful calibration and validation of the model, the model was run. Water balance components namely ET, Surface runoff, lateral flow, ground water flow were extracted from the output of the calibrated model. Their variations with time at an annual and seasonal level were investigated. Spatial variability of the water balance components was also determined.

In order to investigate effects of land cover change on the hydrology of the catchment, five scenarios were created. Scenario I involved conversion of all forest cover to agricultural land in 21 subbasins, Scenario II involved partial conversion (50%) of forest cover to agricultural land in 21 sub basins, Scenario III involved partial conversion (50%) of forest cover to shrub land in 21 sub basins, scenario IV involved conversion of all shrub land to urban land in 3 sub basins while Scenario V involved reduction of shrub land and agricultural land by 25% in favour of forest cover in 25 sub basins.

The results of calibration and validation show the model performed well with R^2 and NSE values of more than 0.5. The hydrological processes that govern the temporal variability of stream flow varied with time. Runoff processes represented by CN2 and surlag were mostly active during peak flows. Canmax was mostly active during resaturation periods while ESCO was mostly active during peak and resaturation periods. Ground water processes were dominant during low, peak and recession flows. Soil processes were mostly active during resaturation and peak segments of the streamflow hydrograph. Results of the comparison of the sensitivities to the FDC curve show that runoff parameters are relatively sensitive during high flow but demonstrate no sensitivity during low flows. Ground water and soil parameters were sensitive in all segments of the FDC. Evaporation parameters are sensitive during intermediate flows. The water balance components varied spatially across the sub basins. The water balance components of the Chania catchment also varied temporally with groundwater taking the largest portion. The average annual precipitation varied from 2376 mm to 1570 mm. The highest precipitation was noted in the year 2002. Surface runoff ranged from 344 mm to 129 mm with the highest value being recorded during the highest precipitation events. Ground water values ranged from 503 mm to 765 mm. Lateral flow values ranged from 291 mm to 510 mm while ET ranged from 670 mm to 850 mm. The water balance components also varied spatially.

Generally, decreasing forest cover led to a reduction in ground water, water yield, ET and lateral flow while increasing surface runoff. Urbanization reduced ground water, lateral flow and ET but lead to an increase in water yield and surface runoff.

5.3 Conclusions

Based on the results, the following conclusions were made.

SWAT model can be used to simulate hydrological processes in the Chania catchment. This is due to the good performance rating of the statistical indices gotten for calibration and validation. There was a good correlation between observed flow values and simulated flow values. For the calibration period, NSE, PBIAS and R^2 values were 0.67, 8.87 and 0.69 respectively, while for the validation period the values were 0.53, 12.24 and 0.59 respectively.

Groundwater and soil processes are dominant hydrological processes which govern the temporal variability of stream flow in Chania catchment. This is deduced from the high presence of sensitivity of groundwater and soil parameters during the TEDPAS analysis. These parameters were also sensitive for longer periods compared to runoff and evaporation parameters. Furthermore, base flow separation indicated a higher percentage of the stream flow was as a result of base flow contribution. The results showed that 74.5% of the stream flow in Chania catchment at station 4CA02 is contributed by base flow. Runoff processes are significant during precipitation events. Evaporation process is significant during peak and re-saturation periods.

The water balance components in Chania catchment vary spatially and temporally. Spatial variation of the water balance components across the watershed is dependent on the amount of precipitation, land cover and type of soil. The temporal variation of all water balance components is dependent on rainfall. Ground water and surface runoff are antagonistic. If one increases, the other reduces and vice versa.

The analysis of land use cover change on hydrology has shown its effects on the hydrology of the Chania catchment. Deforestation exacerbates water scarcity. Deforestation and urbanization lead to reduced groundwater flow. Generally, conversion of forests to agriculture led to the generation of the highest amount of runoff and the highest reduction in ground water. Afforestation on the other hand, led to a reduction in surface runoff. If there is need by the catchment managers to promote practices that reduce generation of runoff, then land used for agriculture should be given first priority. Land under agriculture should be reduced while afforestation should be encouraged. Proper farming practices which seek to optimize land used for agriculture by enabling high yields in a small area should be promoted.

5.4 Recommendations

Calibration of the model was done using stream flow data from a gauging station at the outlet of the catchment. Future hydrological studies requiring calibration should consider using multiple gauging stations. This can be achieved through availability of data. Weather and river gauging stations within and around the catchment should be rehabilitated to enable recording of data. Up to date and complete data can significantly improve modeling results and management of the catchment.

Ground water processes should be protected to sustain low flows. Deforestation and urbanization reduce contribution of precipitation to ground water processes. WRMA should encourage land use policies which protect ground water. Management practices that consider both surface and ground water resources should be employed to better manage future and current water resources in Chania basin. Afforestation should be encouraged to curb water scarcity.

SWAT model as a tool for hydrological modeling can be explored further. Its potential in assessing impacts of climate change on the hydrology of the catchment can be explored.

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APPENDICES

APPENDIX 1-FAST PARAMETERS

	CN	surlag	canmax	ESCO	SOL-AWC	rchrg-deep	gw-delay	alpha-bf
Action	add	replace	add	replace	add	replace	replace	replace
1.00	13.64	1.79	0.63	0.20	0.15	0.07	8.94	0.06
2.00	10.79	1.36	1.90	0.60	0.06	0.21	22.94	0.16
3.00	7.93	0.92	3.17	1.00	0.01	0.25	23.17	0.15
4.00	5.08	0.49	3.57	0.60	0.10	0.11	9.17	0.05
5.00	2.23	0.13	2.30	0.20	0.20	0.03	8.71	0.07
6.00	-0.62	0.56	1.02	0.19	0.11	0.17	22.71	0.17
7.00	-3.47	1.00	0.23	0.60	0.02	0.29	23.40	0.13
8.00	-6.32	1.43	1.50	1.00	0.05	0.15	9.40	0.04
9.00	-9.17	1.86	2.78	0.61	0.15	0.01	8.48	0.08
10.00	-12.02	1.72	3.97	0.21	0.16	0.13	22.48	0.18
11.00	-14.88	1.29	2.69	0.19	0.07	0.27	23.64	0.12
12.00	-12.40	0.85	1.42	0.59	0.00	0.20	9.64	0.03
13.00	-9.55	0.42	0.15	0.99	0.10	0.06	8.25	0.09
14.00	-6.69	0.20	1.11	0.61	0.19	0.08	22.25	0.19
15.00	-3.84	0.63	2.38	0.21	0.12	0.22	23.87	0.11
16.00	-0.99	1.07	3.65	0.19	0.03	0.24	9.87	0.01
17.00	1.86	1.50	3.09	0.59	0.05	0.10	8.02	0.10
18.00	4.71	1.93	1.82	0.99	0.14	0.04	22.02	0.20
19.00	7.56	1.65	0.55	0.62	0.17	0.18	24.10	0.10
20.00	10.41	1.21	0.71	0.21	0.08	0.28	10.10	0.02
21.00	13.26	0.78	1.98	0.18	0.00	0.14	7.79	0.11
22.00	14.01	0.35	3.26	0.58	0.09	0.00	21.79	0.19
23.00	11.16	0.27	3.49	0.98	0.18	0.14	24.33	0.09
24.00	8.31	0.70	2.21	0.62	0.13	0.28	10.33	0.03
25.00	5.45	1.14	0.94	0.22	0.03	0.18	7.55	0.12
26.00	2.60	1.57	0.31	0.18	0.04	0.04	21.55	0.18
27.00	-0.25	2.00	1.59	0.58	0.13	0.10	24.56	0.08

28.00	-3.10	1.58	2.86	0.98	0.18	0.24	10.56	0.04
29.00	-5.95	1.14	3.88	0.62	0.08	0.22	7.32	0.14
30.00	-8.80	0.71	2.61	0.22	-0.01	0.08	21.32	0.17
31.00	-11.65	0.28	1.34	0.17	0.08	0.05	24.79	0.07
32.00	-14.50	0.34	0.07	0.57	0.17	0.19	10.79	0.05
33.00	-12.77	0.78	1.19	0.98	0.13	0.27	7.09	0.15
34.00	-9.92	1.21	2.46	0.63	0.04	0.13	21.09	0.16
35.00	-7.07	1.64	3.74	0.23	0.03	0.01	25.02	0.06
36.00	-4.21	1.94	3.01	0.17	0.12	0.15	11.02	0.06
37.00	-1.36	1.51	1.74	0.57	0.19	0.29	6.86	0.16
38.00	1.49	1.07	0.46	0.97	0.09	0.17	20.86	0.15
39.00	4.34	0.64	0.79	0.63	0.00	0.03	25.26	0.05
40.00	7.19	0.21	2.07	0.23	0.07	0.11	11.26	0.07
41.00	10.04	0.41	3.34	0.17	0.17	0.25	6.63	0.17
42.00	12.89	0.85	3.40	0.57	0.14	0.21	20.63	0.13
43.00	14.38	1.28	2.13	0.97	0.05	0.07	25.49	0.04
44.00	11.53	1.71	0.86	0.64	0.02	0.07	11.49	0.08
45.00	8.68	1.87	0.40	0.24	0.11	0.21	6.40	0.18
46.00	5.83	1.43	1.67	0.16	0.19	0.25	20.40	0.12
47.00	2.98	1.00	2.94	0.56	0.10	0.11	25.72	0.02
48.00	0.12	0.57	3.80	0.96	0.01	0.03	11.72	0.09
49.00	-2.73	0.14	2.53	0.64	0.06	0.17	6.17	0.19
50.00	-5.58	0.48	1.26	0.24	0.16	0.30	20.17	0.11
51.00	-8.43	0.92	0.00	0.16	0.15	0.15	25.95	0.01
52.00	-11.28	1.35	1.27	0.56	0.06	0.01	11.95	0.10
53.00	-14.13	1.78	2.55	0.96	0.01	0.12	5.93	0.20
54.00	-13.14	1.80	3.82	0.64	0.11	0.26	19.93	0.10
55.00	-10.29	1.36	2.93	0.24	0.20	0.20	26.18	0.02
56.00	-7.44	0.93	1.65	0.15	0.11	0.06	12.18	0.11
57.00	-4.59	0.50	0.38	0.55	0.02	0.08	5.70	0.19
58.00	-1.74	0.12	0.88	0.95	0.06	0.22	19.70	0.09
59.00	1.12	0.56	2.15	0.65	0.15	0.24	26.41	0.03
60.00	3.97	0.99	3.42	0.25	0.16	0.10	12.41	0.13
61.00	6.82	1.42	3.32	0.15	0.07	0.04	5.47	0.18
62.00	9.67	1.85	2.05	0.55	0.01	0.18	19.47	0.08
63.00	12.52	1.73	0.78	0.95	0.10	0.28	26.64	0.04
64.00	14.75	1.29	0.48	0.65	0.19	0.14	12.64	0.14

65.00	11.90	0.86	1.75	0.25	0.12	0.00	5.24	0.17
66.00	9.05	0.43	3.02	0.14	0.02	0.14	19.24	0.07
67.00	6.20	0.19	3.72	0.55	0.05	0.28	26.88	0.05
68.00	3.35	0.63	2.45	0.95	0.14	0.18	12.88	0.15
69.00	0.50	1.06	1.17	0.66	0.17	0.04	5.01	0.16
70.00	-2.36	1.49	0.08	0.26	0.07	0.10	19.01	0.06
71.00	-5.21	1.92	1.36	0.14	0.00	0.24	27.11	0.06
72.00	-8.06	1.65	2.63	0.54	0.09	0.23	13.11	0.16
73.00	-10.91	1.22	3.90	0.94	0.18	0.09	4.78	0.14
74.00	-13.76	0.79	2.84	0.66	0.12	0.05	18.78	0.05
75.00	-13.51	0.36	1.57	0.26	0.03	0.19	27.34	0.07
76.00	-10.66	0.26	0.30	0.14	0.04	0.27	13.34	0.17
77.00	-7.81	0.70	0.96	0.54	0.13	0.13	4.55	0.13
78.00	-4.96	1.13	2.23	0.94	0.17	0.01	18.55	0.04
79.00	-2.11	1.56	3.50	0.67	0.08	0.15	27.57	0.08
80.00	0.74	1.99	3.24	0.26	-0.01	0.29	13.57	0.18
81.00	3.60	1.58	1.97	0.13	0.08	0.17	4.31	0.12
82.00	6.45	1.15	0.69	0.53	0.18	0.03	18.31	0.02
83.00	9.30	0.72	0.56	0.93	0.13	0.11	27.80	0.09
84.00	12.15	0.29	1.83	0.67	0.04	0.25	13.80	0.19
85.00	15.00	0.34	3.11	0.27	0.03	0.21	4.08	0.11
86.00	12.27	0.77	3.64	0.13	0.13	0.07	18.08	0.01
87.00	9.42	1.20	2.36	0.53	0.18	0.07	28.03	0.10
88.00	6.57	1.63	1.09	0.93	0.09	0.21	14.03	0.20
89.00	3.72	1.95	0.17	0.67	0.00	0.25	3.85	0.10
90.00	0.87	1.51	1.44	0.27	0.08	0.11	17.85	0.02
91.00	-1.98	1.08	2.71	0.12	0.17	0.02	28.26	0.12
92.00	-4.83	0.65	3.98	0.52	0.14	0.16	14.26	0.19
93.00	-7.69	0.22	2.76	0.93	0.05	0.30	3.62	0.09
94.00	-10.54	0.41	1.49	0.68	0.03	0.16	17.62	0.03
95.00	-13.39	0.84	0.21	0.28	0.12	0.02	28.50	0.13
96.00	-13.88	1.27	1.04	0.12	0.19	0.12	14.50	0.18
97.00	-11.03	1.70	2.31	0.52	0.10	0.26	3.39	0.08
98.00	-8.18	1.87	3.59	0.92	0.00	0.20	17.39	0.04
99.00	-5.33	1.44	3.16	0.68	0.07	0.06	28.73	0.14
100.00	-2.48	1.01	1.88	0.28	0.16	0.08	14.73	0.17
101.00	0.37	0.58	0.61	0.12	0.15	0.22	3.16	0.07

102.00	3.22	0.15	0.64	0.52	0.05	0.24	17.16	0.05
103.00	6.07	0.48	1.92	0.92	0.02	0.10	28.96	0.15
104.00	8.93	0.91	3.19	0.69	0.11	0.04	14.96	0.15
105.00	11.78	1.34	3.55	0.29	0.20	0.18	2.93	0.06
106.00	14.63	1.77	2.28	0.11	0.10	0.28	16.93	0.06
107.00	12.64	1.80	1.01	0.51	0.01	0.14	29.19	0.16
108.00	9.79	1.37	0.25	0.91	0.06	0.00	15.19	0.14
109.00	6.94	0.94	1.52	0.69	0.15	0.14	2.69	0.05
110.00	4.09	0.51	2.79	0.29	0.15	0.28	16.69	0.07
111.00	1.24	0.12	3.95	0.11	0.06	0.18	29.42	0.17
112.00	-1.61	0.55	2.68	0.51	0.01	0.04	15.42	0.13
113.00	-4.46	0.98	1.40	0.91	0.10	0.09	2.46	0.03
114.00	-7.31	1.41	0.13	0.69	0.20	0.23	16.46	0.08
115.00	-10.17	1.84	1.12	0.29	0.11	0.23	29.65	0.18
116.00	-13.02	1.73	2.40	0.10	0.02	0.09	15.65	0.12
117.00	-14.26	1.30	3.67	0.50	0.05	0.05	2.23	0.02
118.00	-11.40	0.87	3.07	0.90	0.15	0.19	16.23	0.09
119.00	-8.55	0.44	1.80	0.70	0.16	0.27	29.88	0.19
120.00	-5.70	0.19	0.53	0.30	0.07	0.13	15.88	0.11
121.00	-2.85	0.62	0.73	0.10	0.00	0.01	2.00	0.01
122.00	0.00	1.05	2.00	0.50	0.10	0.15	16.00	0.11
123.00	2.85	1.48	3.27	0.90	0.19	0.29	30.00	0.20
124.00	5.70	1.91	3.47	0.70	0.12	0.17	16.12	0.10
125.00	8.55	1.66	2.20	0.30	0.03	0.03	2.12	0.02
126.00	11.40	1.23	0.93	0.10	0.04	0.11	15.77	0.12
127.00	14.26	0.80	0.33	0.50	0.14	0.25	29.77	0.19
128.00	13.02	0.37	1.60	0.90	0.17	0.21	16.35	0.09
129.00	10.17	0.26	2.88	0.71	0.08	0.07	2.35	0.03
130.00	7.31	0.69	3.87	0.31	-0.01	0.07	15.54	0.13
131.00	4.46	1.12	2.60	0.09	0.09	0.21	29.54	0.18
132.00	1.61	1.55	1.32	0.49	0.18	0.26	16.58	0.08
133.00	-1.24	1.98	0.05	0.89	0.13	0.12	2.58	0.04
134.00	-4.09	1.59	1.21	0.71	0.04	0.02	15.31	0.14
135.00	-6.94	1.16	2.48	0.31	0.04	0.16	29.31	0.16
136.00	-9.79	0.73	3.75	0.09	0.13	0.30	16.81	0.07
137.00	-12.64	0.30	2.99	0.49	0.18	0.16	2.81	0.05
138.00	-14.63	0.33	1.72	0.89	0.09	0.02	15.07	0.15

139.00	-11.78	0.76	0.45	0.71	-0.01	0.12	29.07	0.15
140.00	-8.93	1.19	0.81	0.31	0.08	0.26	17.04	0.06
141.00	-6.07	1.62	2.08	0.08	0.17	0.20	3.04	0.06
142.00	-3.22	1.95	3.36	0.48	0.14	0.06	14.84	0.16
143.00	-0.37	1.52	3.39	0.88	0.04	0.08	28.84	0.14
144.00	2.48	1.09	2.12	0.72	0.03	0.22	17.27	0.04
145.00	5.33	0.66	0.84	0.32	0.12	0.24	3.27	0.07
146.00	8.18	0.23	0.41	0.08	0.19	0.10	14.61	0.17
147.00	11.03	0.40	1.69	0.48	0.09	0.04	28.61	0.13
148.00	13.88	0.83	2.96	0.88	0.00	0.18	17.50	0.03
149.00	13.39	1.26	3.79	0.72	0.07	0.28	3.50	0.08
150.00	10.54	1.69	2.51	0.32	0.16	0.14	14.38	0.18
151.00	7.69	1.88	1.24	0.07	0.14	0.00	28.38	0.12
152.00	4.83	1.45	0.02	0.48	0.05	0.14	17.74	0.02
153.00	1.98	1.02	1.29	0.88	0.02	0.28	3.74	0.09
154.00	-0.87	0.59	2.56	0.73	0.11	0.19	14.15	0.19
155.00	-3.72	0.15	3.83	0.33	0.19	0.05	28.15	0.11
156.00	-6.57	0.47	2.91	0.07	0.10	0.09	17.97	0.01
157.00	-9.42	0.90	1.64	0.47	0.01	0.23	3.97	0.11
158.00	-12.27	1.33	0.36	0.87	0.06	0.23	13.92	0.20
159.00	-15.00	1.76	0.89	0.73	0.16	0.09	27.92	0.10
160.00	-12.15	1.81	2.17	0.33	0.15	0.05	18.20	0.02
161.00	-9.30	1.38	3.44	0.07	0.06	0.19	4.20	0.12
162.00	-6.45	0.95	3.31	0.47	0.01	0.27	13.69	0.19
163.00	-3.60	0.52	2.03	0.87	0.11	0.13	27.69	0.09
164.00	-0.74	0.11	0.76	0.74	0.20	0.01	18.43	0.03
165.00	2.11	0.54	0.50	0.33	0.11	0.15	4.43	0.13
166.00	4.96	0.97	1.77	0.06	0.02	0.29	13.45	0.17
167.00	7.81	1.40	3.04	0.46	0.06	0.17	27.45	0.08
168.00	10.66	1.84	3.70	0.86	0.15	0.03	18.66	0.04
169.00	13.51	1.74	2.43	0.74	0.16	0.11	4.66	0.14
170.00	13.76	1.31	1.16	0.34	0.07	0.25	13.22	0.16
171.00	10.91	0.88	0.10	0.06	0.01	0.21	27.22	0.07
172.00	8.06	0.45	1.37	0.46	0.10	0.07	18.89	0.05
173.00	5.21	0.18	2.64	0.86	0.19	0.06	4.89	0.15
174.00	2.36	0.61	3.92	0.74	0.12	0.20	12.99	0.15
175.00	-0.50	1.04	2.83	0.34	0.02	0.26	26.99	0.05

176.00	-3.35	1.47	1.55	0.05	0.05	0.12	19.12	0.06
177.00	-6.20	1.91	0.28	0.45	0.14	0.02	5.12	0.16
178.00	-9.05	1.67	0.98	0.86	0.17	0.16	12.76	0.14
179.00	-11.90	1.24	2.25	0.75	0.07	0.30	26.76	0.04
180.00	-14.75	0.81	3.52	0.35	0.00	0.16	19.36	0.07
181.00	-12.52	0.37	3.22	0.05	0.09	0.02	5.36	0.17
182.00	-9.67	0.25	1.95	0.45	0.18	0.12	12.53	0.13
183.00	-6.82	0.68	0.68	0.85	0.12	0.26	26.53	0.03
184.00	-3.97	1.11	0.58	0.75	0.03	0.20	19.59	0.08
185.00	-1.12	1.54	1.85	0.35	0.04	0.06	5.59	0.18
186.00	1.74	1.98	3.12	0.05	0.13	0.08	12.30	0.12
187.00	4.59	1.60	3.62	0.45	0.17	0.22	26.30	0.02
188.00	7.44	1.17	2.35	0.85	0.08	0.24	19.82	0.10
189.00	10.29	0.74	1.07	0.76	-0.01	0.10	5.82	0.19
190.00	13.14	0.30	0.18	0.36	0.08	0.04	12.07	0.11
191.00	14.13	0.32	1.45	0.04	0.18	0.18	26.07	0.01
192.00	11.28	0.75	2.73	0.44	0.13	0.29	20.05	0.11
193.00	8.43	1.18	4.00	0.84	0.04	0.15	6.05	0.20
194.00	5.58	1.62	2.74	0.76	0.03	0.00	11.83	0.10
195.00	2.73	1.96	1.47	0.36	0.13	0.13	25.83	0.02
196.00	-0.12	1.53	0.20	0.04	0.18	0.27	20.28	0.12
197.00	-2.98	1.10	1.06	0.44	0.09	0.19	6.28	0.19
198.00	-5.83	0.67	2.33	0.84	0.00	0.05	11.60	0.09
199.00	-8.68	0.23	3.60	0.76	0.08	0.09	25.60	0.03
200.00	-11.53	0.39	3.14	0.36	0.17	0.23	20.51	0.13
201.00	-14.38	0.82	1.87	0.03	0.14	0.23	6.51	0.17
202.00	-12.89	1.25	0.60	0.43	0.05	0.09	11.37	0.08
203.00	-10.04	1.69	0.66	0.83	0.02	0.05	25.37	0.04
204.00	-7.19	1.89	1.93	0.77	0.12	0.19	20.74	0.14
205.00	-4.34	1.46	3.21	0.37	0.19	0.27	6.74	0.16
206.00	-1.49	1.03	3.54	0.03	0.10	0.13	11.14	0.06
207.00	1.36	0.59	2.26	0.43	0.00	0.01	25.14	0.05
208.00	4.21	0.16	0.99	0.83	0.07	0.15	20.98	0.15
209.00	7.07	0.46	0.26	0.77	0.16	0.29	6.98	0.15
210.00	9.92	0.89	1.54	0.37	0.15	0.17	10.91	0.05
211.00	12.77	1.32	2.81	0.02	0.06	0.03	24.91	0.06
212.00	14.50	1.76	3.93	0.43	0.02	0.11	21.21	0.16

213.00	11.65	1.82	2.66	0.83	0.11	0.25	7.21	0.14
214.00	8.80	1.39	1.39	0.78	0.20	0.22	10.68	0.04
215.00	5.95	0.96	0.12	0.38	0.11	0.08	24.68	0.07
216.00	3.10	0.52	1.14	0.02	0.01	0.06	21.44	0.17
217.00	0.25	0.10	2.41	0.42	0.06	0.20	7.44	0.13
218.00	-2.60	0.53	3.69	0.82	0.15	0.26	10.45	0.03
219.00	-5.45	0.96	3.06	0.78	0.16	0.12	24.45	0.09
220.00	-8.31	1.40	1.79	0.38	0.06	0.02	21.67	0.18
221.00	-11.16	1.83	0.51	0.02	0.01	0.16	7.67	0.12
222.00	-14.01	1.75	0.74	0.42	0.10	0.30	10.21	0.02
223.00	-13.26	1.32	2.02	0.82	0.19	0.16	24.21	0.10
224.00	-10.41	0.89	3.29	0.79	0.11	0.02	21.90	0.19
225.00	-7.56	0.45	3.45	0.38	0.02	0.12	7.90	0.11
226.00	-4.71	0.17	2.18	0.01	0.05	0.26	9.98	0.01
227.00	-1.86	0.60	0.91	0.41	0.14	0.20	23.98	0.11
228.00	0.99	1.03	0.35	0.81	0.16	0.06	22.13	0.20
229.00	3.84	1.47	1.62	0.79	0.07	0.08	8.13	0.10
230.00	6.69	1.90	2.89	0.39	0.00	0.22	9.75	0.02
231.00	9.55	1.68	3.85	0.01	0.09	0.24	23.75	0.12
232.00	12.40	1.25	2.58	0.41	0.19	0.10	22.36	0.18
233.00	14.88	0.81	1.31	0.81	0.12	0.03	8.36	0.09
234.00	12.02	0.38	0.03	0.79	0.03	0.17	9.52	0.03
235.00	9.17	0.24	1.22	0.39	0.04	0.29	23.52	0.13
236.00	6.32	0.67	2.50	0.00	0.14	0.15	22.60	0.17
237.00	3.47	1.10	3.77	0.40	0.17	0.01	8.60	0.08
238.00	0.62	1.54	2.98	0.81	0.08	0.13	9.29	0.04
239.00	-2.23	1.97	1.70	0.80	-0.01	0.27	23.29	0.14
240.00	-5.08	1.61	0.43	0.40	0.09	0.19	22.83	0.16
241.00	-7.93	1.18	0.83	0.00	0.18	0.05	8.83	0.06
242.00	-10.79	0.74	2.10	0.40	0.13	0.09	9.06	0.05
243.00	-13.64	0.31	3.37	0.80	0.04	0.23	23.06	0.15