WATER RESOURCE POTENTIAL INVESTIGATION OF LAKE HAWASSA WATERSHED BY USING A SOIL AND WATER ASSESSMENT TOOL (SWAT)

MSc THESIS

BY

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ADVISORS' APPROVAL SHEET

This is to certify that the thesis entitled "**Water Resource Potential Investigation of Lake Hawassa Watershed by Using A Soil and Water Assessment Tool (SWAT)**" submitted in partial fulfillment of the requirements for the degree of Master of "**Water Resource Engineering and Management**" the Graduate Program of the School of Water Resource and Irrigation Engineering, and has been carried out by "**Jundi Yusuf Abrahim**" ID.No. "WREMR/012/09" under our supervision. Therefore, we recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the School of Water Resource and Irrigation Engineering.

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We, the undersigned, members of the Board of Examiners of the final open defense by **Jundi Yusuf Abrahim** have read and evaluated his thesis entitled "**Water resource potential investigation of Lake Hawassa watershed by using soil and water assessment tool (SWAT)** ", and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Masters in "Water resource engineering and management."

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DECLARATION OF THE FINAL THESIS

I hereby declare that all the corrections and recommendations suggested by the board of examiners are incorporated into the final thesis entitled "**Water resource potential investigation of Lake Hawassa watershed by using soil and water assessment tool (SWAT)**" by Jundi Yusuf Abrahim.

Name of the designate	Signature	date

Lists of Acronyms and Abbreviations

AMC	Antecedent moisture condition
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization.
GIS	Geographic Information System
HEC	Hydrologic Engineering Center
HRU	Hydrologic response unit
IWRM	Integrated water resources management
LPJmL	Lund-Potsdam-Jena managed Land
MWIE	Ministry of Water, Irrigation and Energy
NRCS	National Resources Conservation Service
SCS	Soil Conservation Service
SCSCN	Soil Conservation Service Curve Number
SWAT	Soil and water assessment tool
SWAT-CUP	SWAT Calibration and Uncertainty Programs
SUFI	Sequential uncertainty fitting
UNE	United Nation Environmental Program
WatBal	Water Balance
WEAP	Water Evaluation and Planning System
TMPMX	Average or mean daily maximum air temperature for month (^{0}c)
TMPMN	Average or mean daily minimum air temperature for month (^{0}c)
TMPSTDMX	Standard deviation for daily maximum air temperature for month (^{0}c)
TMPSTDMN	Standard deviation for daily minimum air temperature for month (^{0}c)
PCPMM	Average or mean total monthly precipitation (mmH2O)

PCPSTD	Standard deviation for daily precipitation for month (mmH2O/day)
PCPSKW	Skew coefficient for daily precipitation in month
PR_W1	Probability of a wet day following a dry day in the month
PR_W2	Probability of a wet day following a wet day in the month
PCPD	Average number of days of precipitation in a month
SOLARAV	Average daily solar radiation for month (MJ/m2/day)
DEWPT	Average daily dew point temperature in a month (^{0}c)
WNDAV	Average daily wind speed in a month (m/s)
RAINHHMX	Average or mean daily maximum half hour rainfall

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ABSTRACT

Uncertainties in information about fresh water resource potential have created a critical situation for many countries. Investigating spatiotemporal variability of water resources is, therefore, a critical initial step for water-resource management. Successful planning and management of water resources require the application of effective integrated water resources management (IWRM) models that can solve the encountering complex problems in these multi-disciplinary investigations. In this work, the water resources of Lake Hawassa watersheds were modeled using the Soil and Water Assessment Tool (SWAT), which is a continuous-time, semi-distributed, process-based model. The SWAT-CUP program was used for calibration/validation of the model with uncertainty analysis using the SUFI-2 (Sequential Uncertainty Fitting program) algorithm over the period of 1990-2015 at one gauge station. Parameter transfer method was used from gauged (Tikurwuha) sub catchment to ungauged one. The performance of the SWAT model was evaluated through sensitivity analysis, calibration, and validation. Ten flow parameters were identified to be sensitive for the stream flow of the study area and used for model calibration. The model calibration was carried out using observed stream flow data from 1995 to 2010 and a validation period from 2011 to 2015 years. Both the calibration and validation results showed satisfactory match between measured and simulated stream flow data with the coefficient of determination (R^2) of 0.71 and Nash-Sutcliffe efficiency (NSE) of 0.66 for the calibration, and R^2 of 0.64 and NSE of 0.59 of the validation period. The results reveal that the annual blue-water potential (water yield and deep aquifer recharge) of Lake Hawassa Watershed is 854 million m^3, Whereas the green-water flow (actual evapotranspiration) (ET) is 629 million m^3 and green water storage (soil moisture) is 82 million m^3. Watersheds located around Wondo-Genet yield more blue-water resources compared to watersheds at the western side. The model highlights the water potential of the catchment under current circumstances and gives an insight into its spatiotemporal distribution over the watershed. This study provides a strong basis for the forthcoming studies concerning better water-resources management practices, climate change, and water-quality studies, as well as other socio-economic scenario analyses in the region.

Key words: SWAT, SWAT-CUP, water potential, water availability

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

Water plays a key role in sustaining life on our planet earth. We use water not only for our basic survival (e.g. for drinking, cooking, bathing, and sanitation) but also for many other purposes such as hydropower generation, industry, navigation, and recreation. Water is not only essential for meeting human needs, but it is also needed for nature where it is essentially required to maintain fisheries, wildlife, riparian vegetation, river deltas, and aquatic biodiversity.

As demand for water increases across the world, the availability of freshwater in many regions is likely to decrease due to population growth, industrialization, land use, and climate change. Water withdrawals have increased more than twice as fast as population growth and currently, one-third of the world's population live in countries that experience medium to high water stress. Current concerns about climate variability and climate change demand improved management of water resources to cope with more intense droughts.

Integrated water resources management (IWRM) is a systematic process for sustainable development, allocation and monitoring of water resource use in the context of social, economic and environmental objectives. Therefore, understanding surface water resources potential and use is a key aspect of water resource assessment, evaluation, and development.

Several hydrologic models are widely used for the assessment of the water resource. Rainfall-runoff models have broadly used in hydrology over the last century for a number of applications, and play an important role in optimal planning and management of water resources in catchments. Those models include SCS-CN, HEC-1, HEC-HMS (HEC, 1990, 2001), SWAT, WatBal and the WEAP model.

Among the aforementioned models, the SWAT model is one that applied to a large ungauged basin for quantitatively determining the spatiotemporal variation of water resources (Arnold *et al.,* 1998). SWAT is a process-based and time continuous hydrological model operating on a daily scale. The model is semi-distributed and allows simulation of a high level of spatial detail by dividing the basin into a large number of sub-basins and HRUs (Arnold *et al.,* 1998). The main components of SWAT include hydrology, climate, nutrient cycling, soil processes, sediment movement, crop growth, agricultural management, and pesticide dynamics.

The freshwater cycle can partitioned into two kinds of green and blue water in accordance with the hydrological processes and storage type involved. *Bluewater* flows through either on or below the land surface, and can be stored in aquifers, lakes, and reservoirs, while *Green water* refers to the portion of precipitation that infiltrates to become soil moisture or remains temporarily on top of the soil or vegetation, then eventually returns to the atmosphere via transpiration and evaporation (Falkenmark and Rockström, 2006.).

Green water is differentiated between green-water resources and green-water flows. Green-water resource is the moisture in the soil. This renewable part can potentially generate economic returns and the source of rain-fed agriculture. Green-water flow, however, is the actual evaporation (the nonproductive part) and the actual transpiration (the productive part), commonly referred to together as the actual evapotranspiration. Thus, it is vital to evaluate the blue- and green water potential for human activities.

This water paradigm is successfully used to evaluate water resources and its availability throughout the world using Soil and Water Assessment Tool (SWAT) models at continent, country, or basin scales (Cuceloglu, et al.,2017). Accordingly, the Blue Water represents consumptive use from blue water sources (surface water and groundwater bodies), and the Green Water represents the fraction of green water that is consumed by agricultural lands (e.g. evapotranspiration from crop and permanent pasture areas).

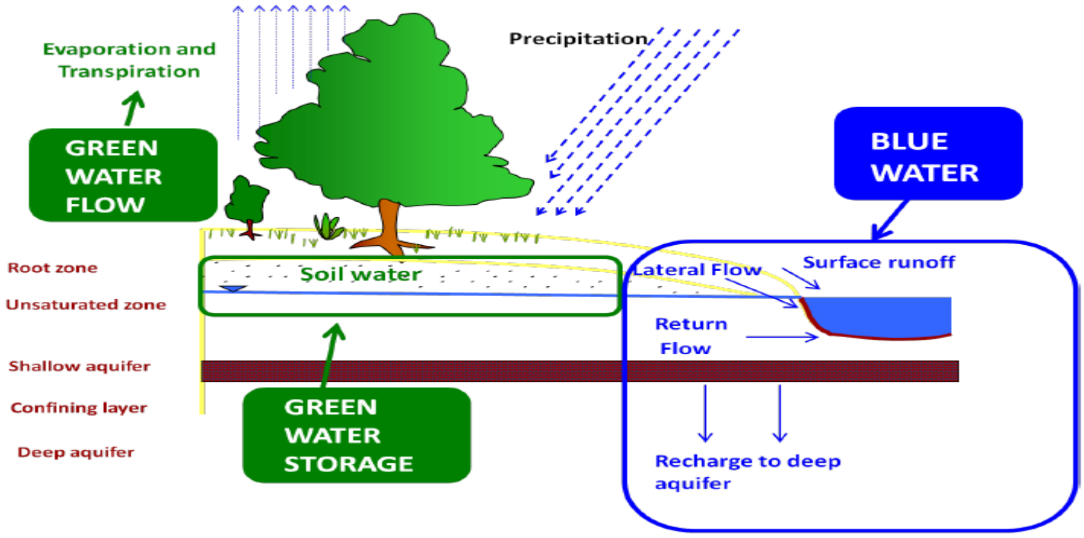

Figure 1.Definition of blue water flow, green water flow, and green water storage (Karim et al., 2010).

Lake Hawassa is located at 275km south of Addis Ababa at the vicinity of Hawassa town, the capital of South Nations ,Nationalities and Peoples Regional State, which is located at (Lat: 6^0 33'-7^0 33' N; Long: 38^0 22' – 38^0 29' E)and at an altitude of 1680 m in the Ethiopian Rift Valley. The lake is a fresh closed lake playing an important role in the lives of many people in the region. It is the source of the commercial fishery and used for recreation with great potential for future agricultural development. Despite its importance in a wide spectrum of purposes, the water resource potential of the lake watershed is poorly understood. Proper assessment of water resource potential of the catchment is extremely essential for any future water resources development. (Esayas, 2010)

In this study, the freshwater resource potential of the Lake Hawassa watershed is assessed using SWAT model and the results will contribute to a better understanding of the paradigm of blue and green water resources and consequently provide useful information for the planning and management of water resources in the Lake Hawassa watershed.

1.2. Statement of the Problem

Climate change due to the greenhouse effect plays a vital role in the availability of freshwater and is just one of the pressures facing water resources today so that quantifying the water resources of a country is essential for providing the strategic information needed for long term planning of the country’s water security. Conventional water-resource planning and management have mostly been based on “blue-water” resources, which serve the needs of engineers who are responsible for coping with infrastructure projects for water supply.

In Lake Hawassa watershed there is increasing demand for water for various activities and inadequate safe water supply in the area including the Hawassa town, **(**Daniel et al., 2015). The river that the town uses as water supply source is from far away area of around Wondo-Genet since groundwater around the town is highly fluoride content and not suitable for drinking purpose. This indicates the uncertainty in the information available regarding the freshwater resource potential, which will be also an option for water supply of an area.

One of the gaps in previous carried out studies is that there is uncertainty about water balance components of the whole watershed by the swat model. Therefore updating this data of water balance for the watershed are very important.

The research helps to know the blue and green water resource of Lake Hawassa watershed. This is a great input for future water resource development.

1.3. Objectives of the Study

1.3.1. General objective

The general objective of this thesis is Quantitative analysis of water resources for Lake Hawassa watershed including all components of the water balance.

1.3.2. Specific objectives

Specific objectives are,

i. To identify areas in Lake Hawassa watershed having high blue water potential.

ii. To study the availability of sufficient green water for ecosystem service and agriculture at different parts of the watershed.

iii. To evaluate the spatial and temporal variation of water resource components at different parts of the watershed.

1.4. Research Questions

To reach the objective of the study, these questions need to be answered; how much water resource is available for development in Lake Hawassa watershed?

The specific research question of the study is formulated as follows:

i. Which parts of the Lake Hawassa watershed experience high blue water?

ii. Which part of the catchment has sufficient precipitation and green water resources to sustain the ecosystems and the development of rain-fed agriculture in those regions?

iii. What is the variation of water resource components over parts of catchments?

1.5. The Significance of the Study

This study provides awareness into the water resource potential of Lake Hawassa watershed in the past. Understanding the variation of the water resource within the watershed, which would help watershed managers, agricultural producers, policymakers. Moreover, it may help in the development of adaptive measures in response to climate change; it may reduce unnecessary losses from the water cycle. It will help with the provision of a reliable water source for food production and human consumption. It will aid the development of sustainable water management strategies that will enable the desired level of functionality within the local ecosystem.

CHAPTER TWO

2. LITERATURE REVIEW

There have been many studies quantifying the green and blue water resources since the advent of the concept. For instance, Gerten et al. (2005) used the LPJ/LPJmL model to estimate global green and blue water consumption over the past 30 years. Faramarzi et al. (2009) adopted the SWAT model to simulate blue and green water resources in Africa and Iran, respectively. Kaisheng Luo and, Fulu Tao., (2016). Hydrological models can provide more insights into the mechanisms of the land surface and hydrological processes, and are regarded as a powerful tool for simulating hydrological processes and assessing water resources spatiotemporally.

There are many kinds of research or studies done on the lake Hawassa watershed related to the water resources. Some explanation about them is as given below.

2.1. Blue Water Resource in Lake Hawassa Watershed

Habtom Gebremichael (2007) makes one of the studies. The study was done to investigate the causes of Lake water level rise and to find remedial solutions to the causes of Lake water level rise. In the report, the runoff from the catchment area feeds Lake Hawassa in two different ways. The northern, southern and Western part of the basin areas are poorly drained and feed the lake as an overland flow without well-defined channel except in the Southwestern part where few gullies are developed. The flat lying, thick and fertile agricultural land infiltrates the dispersed overland flow from the highlands. Due to the flatness of the plain agricultural land, west of the lake, no significant surface runoff can be expected to enter the lake. While the eastern and southeastern part of the drainage area has a relatively dense drainage pattern and all the runoff from this catchment feeds Lake Shallow (Cheleleka) and the adjacent swampy area, overflow from Lake Shallo drains into Lake Hawassa through Tikurwuha River.

According to the studies made by Daniel et al., (2015)**,** It is found that there is inadequate safe water supply in the watershed since more than 40% of the communities in the rural part of the catchment do not have access to potable water and relied on an unimproved water source, such as rivers, streams, and the Lake. Therefore, it is concluded from the report that investigating and quantifying the freshwater resource components in terms of blue and green for each subwatershed is crucial to meet the increasing demand for water for various activities.

According to the studies made by Mulgeta Dadi (2013), the study was done to investigate causal variables for lake level variability in general, and its resultant rise in particular. In the report it is estimated that the long-term average annual magnitudes of the water balance components as follows: over-lake precipitation (89 Mm^3), evaporation from the lake surface (132 Mm^3), stream flow from the Tikurwuha sub-watershed (94 Mm^3), and stream flow from the un-gauged sub-watershed (77 Mm^3) and storage changes (three Mm^3).

According to the studies made by (Esayas, 2010), in the report, the total amount of net water yield from the catchment in 2004 has increased by 1.89% from that of 1965.

2.2. Green Water Flow and Storage of the Area

Telford developed a steady state water balance for Lake Hawassa watershed and suggests that direct precipitation accounted for 56% of the total input and 44% of runoff. Evaporation dominates losses from the lake (93%) but there is some groundwater seepage (7%). Esayas, (2010).Yemane, (2004) study the water balance of Lake Hawassa on monthly bases and quantified the evaporation from catchment as 131 Mm3.

2.3. Assessment of the Water Balance of Lake Hawassa Catchment

Yamane carried out the study in 2004. The study quantified the water balance components of the Lake Hawassa and its catchment on monthly bases. The study is based on the use of the Thornthwaite and Mather soil water balance procedure and developed a spreadsheet model of the catchment and the lake water balances for the period of 1981-1998. Based on the simulation results he found the annual average water balance components such as evaporation, rainfall, surface runoff, and constant groundwater outflow and estimated 131, 106, 83 and 43 Mm^3 respectively. The results of the Lake and catchment water balance analysis show that the combined effect of climatic and land use changes during the past 25 years most likely resulted in an increase of the catchment runoff and so the lake level.

Despite many types of research done previously on the area, there is a gap in systematic modeling of the water resources of Lake Hawassa watershed to quantify both the potential of all watersheds in supplying potable water and to assess water availability in terms of various components of the water budget with a high resolution. This study has been conducted to fill this gap.

2.3. Hydrological Models

Hydrological models are tools that describe the physical processes controlling the transformation of precipitation to stream flows. There are different hydrological models designed and applied to simulate the rainfall-runoff relationship under different temporal and spatial dimensions. The focus of these models is to establish a relationship between various hydrological components such as precipitation, evapotranspiration, surface runoff, groundwater flow and soil water movement (infiltration). Many of these hydrological models describe the canopy interception, evaporation, transpiration, and snowmelt, interflow, overland flow, channel flow, unsaturated subsurface flow, and saturated subsurface flow. These models range from simple unit hydrograph based models to more complex models that are based on the dynamic flow equations. (Esayas, 2010).

Simulation programs implementing watershed hydrology and river water quality models are important tools for watershed management for both applied and operational research purposes. A hydrological model represents the water cycle of a drainage basin and studies the response of this basin to climatic and physical conditions (Renaud, 2004). Three different categories of hydrological models can be distinguished: physically process based, empirical and statistically based.

Mathematically formulated fundamental physical laws describe physically process-based models, where each basin is represented by a concept, a reservoir for instance. They are useful for inferring the distribution, magnitude, and past, present and future behavior of a process with limited observations. These equations can relate the changes of water properties into the reach to those across the surface. (Esayas, 2010).

Empirical models are a synthesis and a summary of field or experimental observations. Their fundamental parameters are not compulsory physically related. Empirical models are based on defining important factors through field observation, measurement, experiments, and statistical methods. They are useful in predicting the hydrology or soil erosion, but are site specific and require long-term data. Empirical models are the result of several years of research data and numerically evaluate the effects of climate, soil properties, topography and crop management.

Physically based models are based on knowledge of the fundamental processes and incorporate the laws of conservation of mass and energy. These physical processes vary both temporally and spatially. They consider the spatial and temporal changes of different factors (Jaroslav et al., 1996). Physically based distributed watershed models play a major role in analyzing the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds.

In recent years, distributed watershed models are increasingly used to study alternative management strategies in the areas of water resources allocation, flood control, the impact of land use change and climate change, and finally environmental pollution control. Many of these models share a common base in their attempt to incorporate the heterogeneity of the watershed and spatial distribution of topography, vegetation, land use, soil characteristics, rainfall, and evaporation.

Some of the watershed models developed in the last two decades are, CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) , EPIC - Erosion Productivity Impact Calculator (Williams, 1995), AGNPS (Agricultural None Point Source model) , SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998) and HSPF (Hydrologic Simulation Program – Fortran), ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation) (Beasley and Huggins, 1982), EROSION-3D (SCHMIDT, 1995), EUROSEM (European Soil Erosion Model), WEPP (Water Erosion Prediction Project) etc. Many of these watershed models are applied for runoff and soil loss prediction Esayas, (2010).

Table 1.Description of three selected hydrological models

Description	SWAT	WetSpass	HBV
Model type	Semi-distributed Physically-based Long-term	Semi-distributed Physically-based	Semi-distributed Conceptual model
Model objective	Predict the impact of land management practices on water and sediment	Simulate ground water, evapotranspiration, runoff, interception process of watershed	Simulate rainfall-runoff process and floods
Temporal scale	Day +	Day -	Day -
Spatial scale	Medium +	Flexible	Flexible
Process modeled	Continuous	Continuous & event	Continuous & event
Cost	Public domain	Public domain	Public domain

Among the above-mentioned models, the physically based distributed model SWAT is a well-established model for analyzing the water resource potential including all water balance components for large complex watersheds

2.3.1. SWAT model description

The Soil and Water Assessment Tool (SWAT) Model was developed by the USDA Agricultural Research Service. This model is a watershed scale model that can predict the impact of changes in land management on water and sediment. It is physically based requiring specific information about soil, topography, weather, and land management practices within the watershed (Arnold et al., 1998). SWAT is a useful tool because watersheds that do not have any monitoring data can be modeled. It also can simulate large watersheds in a relatively short period of time (Arnold et al., 1998). The Soil and Water Assessment Tool is a physically based and semi-empirical model. It is based on physical laws but it also permits the addition of measurements and their use for simulations. The spatial areas that can be modeled range from hundreds to thousands of square kilometers. Esayas, (2010).

Water balance is the driving force behind all the processes in SWAT because it affects plant growth and the movement of sediments, nutrients, pesticides, and pathogens. In SWAT, a

Watershed is divided into multiple sub-basins, which are then further subdivided into hydrologic response units (HRUs) based on unique combinations of land use, soil, management, and topographical features. The model simulates hydrology of a watershed in two phases. In the first phase, called the land phase, the hydrological processes of a watershed are simulated at the HRU level and water balance calculated for each sub-basin. The pathways of water movement in the land phase simulated by SWAT are given as canopy storage, surface runoff, evapotranspiration, infiltration, lateral sub-surface flow, and return flow, revap from shallow aquifers and percolation to the deep aquifer. In the second phase (the routing phase), after the loadings of water, sediment, nutrients, and pesticides are determined, and loadings are routed through streams and reservoirs within the watershed (Cuceloglu et al.,20170) A schematic representation of hydrological cycle elements simulated by SWAT is given in the figure below.

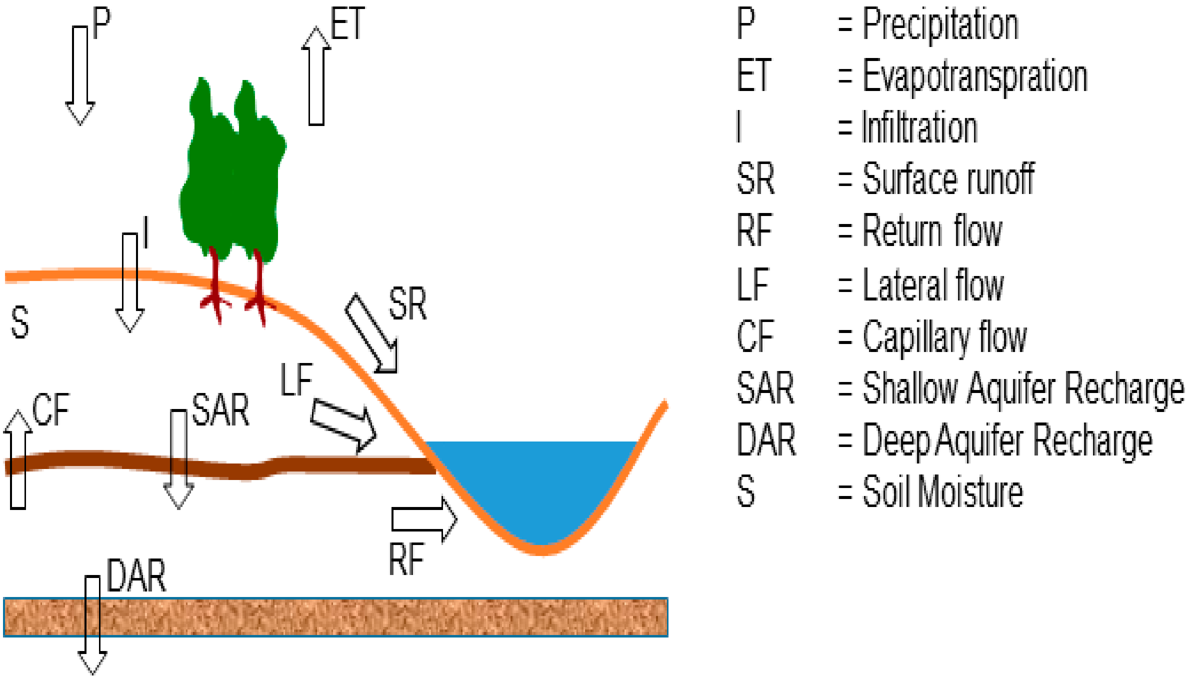

Figure 2. Schematic representation of hydrological cycle elements in SWAT (source: Cuceloglu et al.,2017)

An important issue to consider in the prediction of hydrology, sediment yield, and water quality is uncertainties in the predictions. The main sources of uncertainties are:

Simplifications in the conceptual model. For example, the simplifications in a hydrologic model, or the assumptions in the equations for estimating surface erosion and sediment yield, or the assumptions in calculating flow velocity in a river, Processes occurring in the watershed but not included in the model. For example, wind erosion, soil losses caused by landslides,Processes that are included in the model, but their occurrences in the watershed are unknown to the modeler or unaccountable; for example, reservoirs, water diversions, irrigation, or farm management affecting water quality, Processes that are not known to the modeler and not included in the model. These include dumping of waste material and chemicals in the rivers, or processes that may last for a number of years and drastically changes the hydrology or water quality such as constructions of roads, bridges, tunnels and dams, and Errors in the input variables such as rainfall and temperature Esayas, (2010).

2.3.2. SWAT model application worldwide

The SWAT model has a good reputation for best use in agricultural watersheds and its uses have been successfully calibrated and validated in many areas of the USA and other continents (Ndomba, 2002; Tripathi *et al.*,2003). The studies indicated that the SWAT Model is capable of simulating the hydrological process and erosion/sediment yield from complex and data poor watersheds with reasonable model performance statistical values. Ndomba (2002) was applied the SWAT model in the modeling of Pangari River (Tanzania) to evaluate the applicability of the model in complex and data poor watersheds. Tripathi *et al.*, (2003) applied the SWAT model for Nagwan watershed in India with the objective of identifying and prioritizing of critical sub-watersheds to develop an effective management plan and the model was verified for both surface runoff and sediment yield. Accordingly, the study concluded that the SWAT model could be used in ungauged watersheds to simulate the hydrological and sediment processes.

SWAT has gained international acceptance as a robust interdisciplinary watershed modeling tool as evidenced by international SWAT conferences, hundreds of SWAT related papers presented at numerous other scientific meetings, and a large number of articles published in peer-reviewed journals (Gassman, 2007).

However, Cibin *et al.* (2010) indicated that SWAT model parameters show varying sensitivity in different years of simulation suggesting the requirement for dynamic updating of parameters during the simulation. The same study also indicated that sensitivity of parameters during various flow regimes (low, medium and high flow) is also found to be uneven, which suggests the significance of a multi-criteria approach for the calibration of the model.

2.3.3. SWAT model application in Ethiopia

The SWAT model application was calibrated and validated in some parts of Ethiopia, frequently in the Blue Nile basin. Through the modeling of Gumara watershed (in Lake Tana basin), Awulachew *et al.* (2008) indicated that streamflow and sediment yield simulated with SWAT were reasonably accurate. The same study reported that similar long-term data could be generated from ungauged watersheds using the SWAT model. A study conducted on the modeling of the Lake Tana basin with the SWAT model also showed that the SWAT model was successfully calibrated and validated (Setegn *et al.,* 2008). This study reported that the model could produce reliable estimates of streamflow and sediment yield from complex watersheds. Gessese (2008) used the SWAT model performed to predict the Legedadi reservoir sedimentation. According to this study, the SWAT model performed well in predicting sediment yield to the Legedadi reservoir. The study further put that the model proved to be worthwhile in capturing the process of streamflow and sediment transport of the watersheds of the Legedadi reservoir.

In addition to the above, Setegn et al., (2008), tested the SWAT model for prediction of sediment yield in Anjeni gauged watershed. The study found that the observed values showed a good agreement at Nash-Sutcliff efficiency (ENS) of 80 %. In light of this, the study suggested that the SWAT model could be used for further analysis of different management scenarios that could help different stakeholders to plan and implement appropriate soil and water conservation strategies. The SWAT model showed a good match between measured and simulated flow and sediment yield in Gumara watershed both in calibration and validation periods (Asres and Awulachew, 2010). Tekle (2010) through modeling of Bilate watershed also indicated that SWAT Model was able to simulate streamflow at reasonable accuracy. The literature reviewed and presented above showed that SWAT is capable of simulating hydrological and soil erosion process with reasonable accuracy and can be applied to large and complex watersheds.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Geographical location of the Hawassa Lake and Its watershed

Lake Hawassa is located at 275km south of Addis Ababa at the vicinity of Hawassa town, the capital of South Nations and Nationalities and Peoples Regional State, which is located at (Lat: 6^0 33'-7^0 33' N; Long: 38^0 22' – 38^0 29' E)and at an altitude of 1680 m in the Ethiopian Rift Valley.

Lake Hawassa is the smallest (96 km^2) of the eight major Lakes found in the rift valley of Ethiopia. Mulugeta Dadi (2013) has found that the maximum depth of Hawassa Lake is 23.4m with an average depth of 11 m. The Lake drains an area of 1250km^2 and can accommodate 1.036 x 109 m^3 of water. It lacks any obvious outlet but is fed by a small river, the TikurWuha river that has a drainage area of about 706 km2, which is being gauged since 1989 (Esayas, 2010).

Lake Hawassa is a Caldera Lake, which occupies the lowest elevation in the Lake catchment. The Lake occupies about 7% and the Hawassa town covers 1% of the total watershed. The study area consists of two major areas, namely, the Lake Hawassa, as well as, the watershed area, which is the principal intention of the present study. The Lake catchment falls into two regions, Southern Nation, Nationalities and Peoples' Regional State (SNNPRS) and Oromiya regional state (ORS). It lies between latitude 6º48'45" – 7º14' 49"N, and longitude 38º16'34" – 38º43'26"E. Elevation of the area generally ranges from 1680 to 2600 m.a.s.l. The catchment area comprises escarpments, ridges, plateau, plains (undulating to rolling and dissected), depressions and swamps. Conversely, as Lake Hawassa is situated at the highest altitude (1680 m.a.s.l.) than other Lakes in the rift valley. The groundwater from Lake Hawassa is bound to flow to low lying Lakes in the region [e.g., Lake Ziway (1636 m.a.s.l.), Langano (1585 m.a.s.l.), Abijata (1578 m.a.s.l.), Shalla (1550 m.a.s.l.) and Abaya and Chamo (~1180 m.a.s.l.)] if hydro-geological condition permits (Gebreegziabher, 2004 cited in Mulugeta Dadi, 2013,).

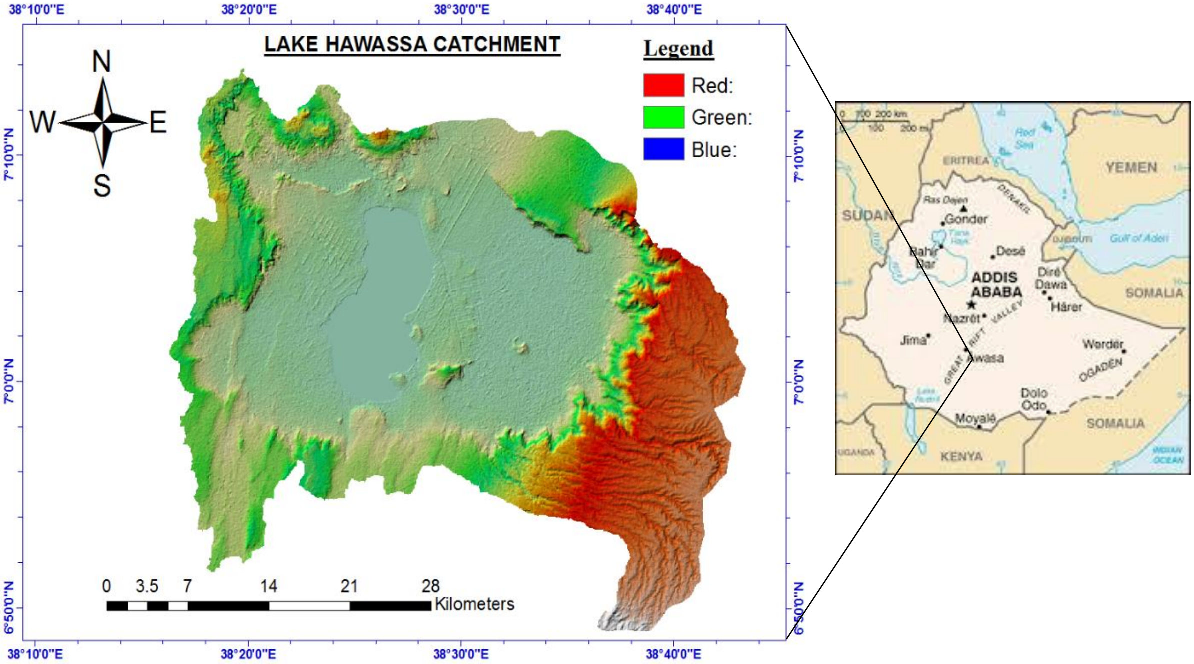

Figure 3. Closed basin of Lake Hawassa Watershed (Source: Getachew et al., 2015)

The watershed comprises seven woredas from SNNPRS and four woredas from Oromiya region. The area coverage of each woreda is presented in Table 2 below.

Table 2. Administrative structure of Lake Hawassa Watershed (Source: Daniel et al., 2015)

Region	Zone	Woreda	Area(km^2)	%
SNNPRS	Sidama	Hawassa Boricha Shebedino Wondo Genet Melga Gorje Hawassa Zuria	254.8 94.6 39.8 227.4 150.4 56.7 155.5	69.5
Oromiya	West Arsi	Shashamane Shalla Siraro Kofele	188.3 74.8 51.9 23.6	30.5

3.1.2. Land use and land cover

The eastern highlands are moderately vegetated and the lowlands close to the foot of the escarpment are relatively well covered with mixed type vegetation, while the poorly drained western part of the catchment is devoid of vegetation and it is severe in the high lands. The North West mountainous area formed of an obsidian rock formation is covered with dense bush.

The mainland use of the sub-basin is rain-fed agriculture of annual and perennial crop with the small area of mechanized farms at the shala and Hawassa state farms. Cheleleqa marshlands to the east of Hawassa town serve as grazing land.

3.1.2.1 Soil Classification

The soil classification is based on the physical and chemical characteristics which include depth, color, structural development, texture and evidence of profile development such as presence of diagnostic horizons, reaction to 10% HCL, pH value and others. The soil types described in the document with respect to their position in a different relief intensity and slope are Vitric Andosols, Vertic Cambisols, Pellic Vertisols, Orthic Luvisols, Mollic Andosols, Leptosols, Leptisol and Regos, Humic Glyesols, Eutric vertisols, Eutric Fluvisols, Chromic Vertisols, Chromic Luvisols and Calcic Xerosols. Administrative structure of the catchment is described in the table below.

3.1.3. Climate

From the climatic classification map of Ethiopia, Tropical Climate dominates the climate of the watershed with distinct dry winter in the western part of the study area and Warm Temperate Rainy Climate in the eastern part highlands of the project area. Based on the Moisture Index Classification of climate, the climate of the watershed, in general, is dry sub-humid in the northern part of the high lands and moist sub-humid in the eastern and southern part of the catchment area.

a) Rainfall

The moisture for precipitation in the area originates from a southwest equatorial air stream, which moves northwards with inter-tropical convergence zone (ITCZ), (WWDSE, 2001). June to September rainfall contributes 44% to the mean annual precipitation in the catchment. The climate in the area is dry to sub-humid according to the Thornthwaite’s system of defining climate or moisture regions, (Dessie Nadaw, 1995). The mean annual rainfall on bases of 12 to 30 years of record of five rainfall stations that contribute to the catchment is estimated to be 1038mm. Both the amount and seasonality of the rainfall show some variability. The wettest months are April, May and September presented in the following (figure 4).

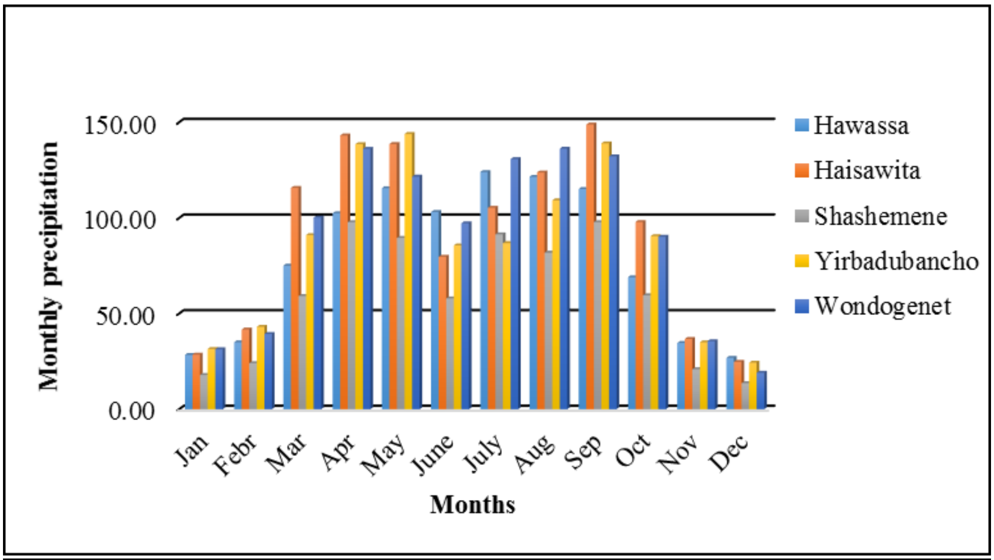

Figure 4. Long-term mean monthly rainfall of different station (1990-2015)

b) Temperature

The mean annual temperature in Hawassa lies between 15°c -20°c the highest temperature found in the low land area of the catchment. The hottest month is in spring before the rain starts in March and April, with mean monthly temperatures in lowlands around Lake Hawassa laying in the range 20°c -25°c and falling to 15°c -25°c in the high lands. Temperature lowers during the rainy season and coldest month are July and December, with temperatures in the range 15°c -20°c in the low land and 10°c -15 °c in the highest part of sub-basin (Halcrow, 2008) presented in the following (figure 5).

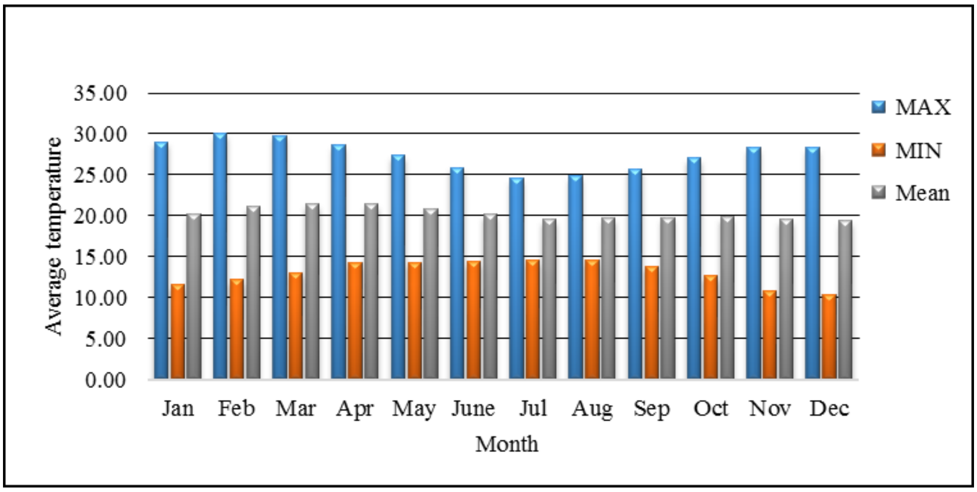

Figure 5. Long-term maximum, minimum and mean monthly temperature (1990-2015)

3.1.4. Geology of the area

The main Ethiopian Rift Valley is divided based on structural features into three geographic areas; represented by the northern (Fentale Nazret), Central (Nazret Hawassa) and southern (Hawassa-Konso) sectors. The central sector, where the Hawassa lake catchment belongs to is asymmetric rift basin where both sides of the rift margins are fully defined except in the region between guraghe and Sodo of the western escarpment and the Shashemene area of the eastern margin (Tadesse, and Zenaw, 2003). The closed catchment of the nested Hawassa Korbeti caldera complex is a giant elliptical depression 30-40kms wide. The Korbeti caldera, which is found northwest of Lake Hawassa, is nested caldera within Hawassa caldera. It has two volcanic centers of Urgi and Chebbi. The Urgi center is a source for the formation of pumice in the vicinity and Chebbi is a center of formation of obsidian, which covers the Chebbi Mountain. (Dessie, 1995), stated the main formations in the area subdivided into four lithological units as follows; Volcano lacustrine deposits, which cover most part of the floor of the depression, composed mostly of volcanic origin (tuff, pumice, ash) with a small amount of diatomite, Recent acidic volcanic, which covers a large part of the north and northwestern part of the catchment where glassy rhyolite rocks superimposed and form massive domes and thick obsidian flows, Basaltic lava flows, scoria and hyaloclastite, which are observed sprinkled on the flat catchment floor forming conical shapes, Ignimbrite of the rift floor and the rift scarp, which is common rock type for the region and covers the east, southwest and the southern part of the catchment where the top few meters of the rock is weathered and fractured in places with columnar joints.

3.1.5. Sub catchment and drainage

The sub-catchment delineation reveals Derba, Muleti, Jara-Mekbasa, Wondo Genet, Wondo Kosha and Toga-Weransa sub-catchments. About 47% of the catchment is covered by Wondo Genet sub-catchment which is relatively less degraded and about 3% of the catchment is by Derba sub-catchment which is highly degraded (Table 3). With regard to the drainage network, the perennial river is found on the eastern part of the catchments (mainly within Wondo Genet sub-catchment) and the seasonal one is on the western part.

Table 3. Area Coverage of Lake Hawassa Sub-Watershed (Source: Daniel et al., 2015)

No	Sub-catchments	Area(km^2)	%
1	Derba	40	2.8
2	Muleti	121	8.6
3	Jara-Mekbesa	419	29.6
4	Wondo Genet	664	47.0
5	Wondo kosha	102	7.2
6	Toga-Weransa	65	4.6
	Total	1411	100

3.1.6. Software and tools used for the study

For the success of this research, different software and tools were used. Those software and tools with their purpose were indicated in table 4.

Table 4. Software and tools used for the study

№	Software and Tools	Purpose
1	Arc GIS 10.3.1	Spatial data processing and to run arc SWAT software
2	Arc SWAT 2012_10.3.19	Hydrologic modeling purpose
3	Rainbow 2.2	Climatic data homogeneity test
4	MS Excel and Word 2016	Writing and graphing and calculations
5	SWAT-CUP 5.1.6.2	Model Calibration, sensitive analysis and validation
6	pcpSTAT.exe	For calculation of weather generator parameter
7	Dew02.exe	Calculation of dew point

3.2. Hydrological Model Selection Criteria

There are various criteria, which can be used for choosing the right hydrological model for a specific problem. These criteria are project dependent since every project has its own specific requirements and needs. Further, some criteria are also user-depended (and therefore subjective). Among the various project-dependent selection criteria, there are four common, fundamental ones that must be always answered (Cunderlik, 2003) these are; Required model outputs important to the project and therefore to be estimated by the model (Does the model predict the variables required by the project such as a long-term sequence of flow?), Hydrologic processes that need to be modeled to estimate the desired outputs adequately (Is the model capable of simulating single-event or continuous processes?), Availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?), Price (Does the investment appear to be worthwhile for the objectives of the project?).

3.2.1. Reasons for selecting the SWAT model

The reasons behind for selecting the SWAT model for this study are; the model is physically based distributed model and well established for analyzing the water resource potential over other models. The model was applied for land use and land cover change impact assessment in different parts of the world. The model simulates the major hydrological process in the watersheds. It is less demanding on input data, and It is readily and freely available. A major limitation to large area hydrologic modeling of SWAT is the spatial detail required to correctly simulate environmental processes. For example, it is difficult to capture the spatial variability associated with precipitation within a watershed.

Another limitation is data files can be difficult to manipulate and can contain several missing records. The model simulations can only be as accurate as the input data.

3.3. Hydrological Component of SWAT

The Simulation of the hydrology of a watershed is done in two separate divisions (Caroline, 2013). One is the land phase of the hydrological cycle that controls the amount of water and sediment loadings to the main channel in each subwatershed. Hydrological components simulated in land phase of the Hydrological cycle are canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds, tributary channels and return flow. The second division is the routing phase of the hydrologic cycle that can be defined as the movement of water and sediments through the channel network of the watershed to the outlet (Caroline, 2013). In the land phase of the hydrological cycle, SWAT simulates the hydrological cycle based on the water balance equation (Caroline, 2013) as equation 3.1.

$$SW_t = SW_0 + \sum_{i=0}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \qquad (Eq. 3.1)$$

Where, $SW_t$is the final soil water content (mm),SW_0 is the initial soil water content on day i (mm), $t$is the time (days),$R_{day}$is the daily precipitation on a day i(mm),Q_{surf} is the amount of surface runoff on a day i(mm), $E_a$is the evapotranspiration on a day i(mm), W_{seep} is the amount of water entering the unsaturated zone on a day i(mm) and consists of the infiltration rate minus the capillary rise, and Q_{gw} is the amount of return flow on a day i(mm).

3.3.1. Components of stream flow

Surface runoff

Surface runoff refers to the portion of rainwater that is not lost to interception, infiltration, and evapotranspiration (Solomon, 2005). Surface runoff occurs whenever the rate of precipitation exceeds the rate of infiltration. SWAT offers two methods for estimating the surface runoff: the Soil Conservation Service (SCS) curve number method and the Green and Ampt infiltration method. The Green and Ampt method needs sub-daily time step rainfall, which made it difficult to be used for this study due to unavailability of sub-daily rainfall data. Therefore, the SCS curve number method was adopted for this study. The general equation for the SCS curve number method is as equation 3.2 below.

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad (Eq3.2)$$

Where, Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mmH_2O), I_a is initial abstraction which includes surface storage, interception and infiltration prior to runoff (mmH_2O) and$S$ is retention parameter (mmH_2O).The retention parameter varies spatially due to changes in land surface features such as soils, land use, slope and management practices. These parameters also can be affected temporally due to changes in soil water content. It is mathematically expressed as in equation 3.3 below.

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (Eq. 3.3)$$

Where, $CN$is the curve number for the day and its value is the function of land use practice, soil permeability and soil hydrologic group. The initial abstraction I_a, is commonly approximated as $0.2S$ and equation 3.2 becomes the following equation 3.4 below.

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - 0.8S)} \qquad (Eq. 3.4)$$

Runoff will only occur when $R_{day} > I_a$

Lateral flow/Interflow

Once the surface runoff is calculated from rainfall, the remaining amount of water is allowed to infiltrate in soil layers. The infiltrated water is then routed through soil layers by the storage routing methodology (Han *et al.*, 2012; Neitsch *et al.*, 2011). The storage routing method first fulfils the field capacity requirement of the upper soil layer and calculates if there is excess soil water available. If there is excess soil water available then the lateral flow from an HRU is calculated as equation 3.5.

$$Q_{lat} = 0.024\left(\frac{2 * SW_{ly.excess} * K_{sat.ly} * slp}{\emptyset_d * L_{hill}}\right) \qquad (Eq. 3.5)$$

Where, $K_{sat.ly}$ is saturated hydraulic conductivity (mm/hr.), slp is the steepness of a slope (m/m), $\emptyset_d$ is the drainable porosity of soil layer(mm/mm), $SW_{ly.excess}$ is the water content in a soil layer above the field capacity (mm), and L_{hill} is the hill slope length(m).

Base flow/Return flow

To simulate the groundwater SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and deep, confined aquifer which contributes return flow to streams outside the watershed (Neitsch *et al.*, 2011). In SWAT the water balance for a shallow aquifer is shown in the following equation 3.6.

$$aq_{sh,i} = aq_{sh,i-1} + W_{rchg} - Q_{gw} - W_{revap} - W_{deep} - W_{pump,sh} \qquad (Eq. 3.6)$$

Where, $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day i (mm), $aq_{sh,i-1}$ is the amount of water stored in the shallow aquifer on day $i-1$ (mm), W_{rchg} is the amount of recharge entering the aquifer on day i(mm), Q_{gw} is the groundwater flow, or base flow, or return flow, into the main channel on day i (mm), W_{revap} is the amount of water moving into the soil zone in response to water deficiencies on day i (mm), W_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm), and $W_{pump,sh}$ is the amount of water that is removed from the shallow aquifer by pumping on day i (mm).The shallow aquifer contributes base flow to the main channel or reaches within the sub-basin. The steady-state response of groundwater flow to stream flow is shown in equation 3.7.

$$Q_{gw} = \frac{8000 * K_{sat}}{L_{gw}2} * h_{wtbl} \qquad (Eq. 3.7)$$

Where, Q_{gw} is the groundwater flow or base flow into the main channel on day *i* (mmH_2O), K_{sat} is the hydraulic conductivity of aquifer(mm/day), L_{gw} is the distance from the ridge or sub basin divide for the groundwater system to the main channel(m) and h_{wtbl} is the water table height(m).

Flow routing

Two options are available to route the flow in the channel network: the variable storage and Muskingum methods. The variable storage method uses a simple continuity equation in routing the storage volume, whereas the Muskingum routing method models the storage volume in a channel length as a combination of wedge and prism storages (Arnold *et al.*, 1995).For a given reach segment, storage routing is based on the continuity equation 3.8 .

$$V_{in} - V_{out} = \Delta V_{stored} \qquad (Eq. 3.8)$$

Where, V_{in} is the volume of inflow during the time step (m^3H_2O), V_{out} is the volume of outflow during the time step (m^3H_2O) and ΔV_{stored} is the change in the volume of storage during the time step (m^3H_2O).

3.3.2. Potential evapotranspiration

Potential Evapotranspiration is a collective term that includes evaporation from the plant (transpiration) and evaporation from the water bodies and soil. Evaporation is the primary mechanism by which water is removed from a watershed. An accurate estimation of evapotranspiration is critical in the assessment of water resources and the impact of land use change on these resources.

Many methods are developed to estimate potential evapotranspiration (PET). SWAT provides three options for PET calculation: Penman-Monteith (Monteith, 1965), Priestley-Taylor (Priestley and Taylor, 1972), and Hargreaves (Hargreaves *et al.*, 1985) methods. The methods have various data needs of climate variables. Penman-Monteith method requires solar radiation, air temperature, relative humidity and wind sped; the Priestley-Taylor method requires solar radiation, air temperature, and relative humidity, whereas the Hargreaves method requires air temperature only. For this study, the Penman-Monteith method was selected as the method is widely used and all climatic variables required by the model are available for the five stations in and around the study watershed area.

3.4. Analytical Framework

In order to achieve the objectives, SWAT model integrated with remote sensing data and GIS techniques were used for simulating the catchment and quantify water resource potential of the Lake Hawassa watershed.

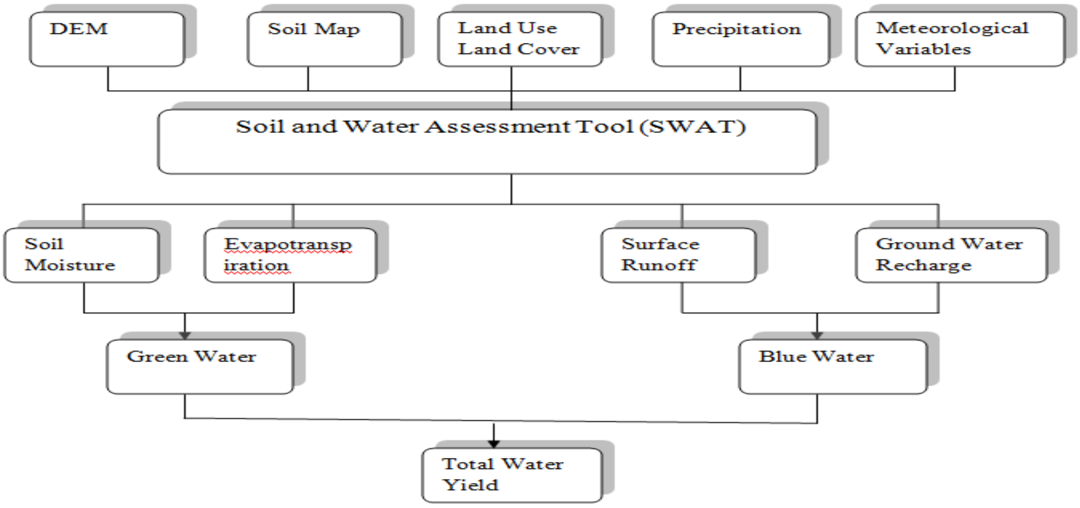

Figure 6. Methodological framework of the SWAT model

3.5. Model Input Data Collection and Analysis

For this study various data were required that include topographic data (DEM), land use and land cover data, soil data, stream flow data, daily data of climatic variables (daily data of precipitation, maximum and minimum temperature, relative humidity, wind speed and solar radiation). The DEM, soil and hydrological data were collected from the Ministry of Water Resources and Energy of Ethiopia. The climatic data were obtained from the National Meteorological Agency of Ethiopia and Global weather data from the SWAT website.

3.5.1. Digital elevation model

Topography was defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. A 20 m by 20m resolution ASTER Global Digital Elevation Model was obtained from the Ministry of Water Resources and Energy of Ethiopia. This data was projected to Transverse Mercator (UTM) on a spheroid of WGS84 and it was in raster format to fit into the model requirement. Subbasin parameters such as slope gradient, slope length of the terrain, and the stream network characteristics such as channel slope, length, and width were derived from the DEM.

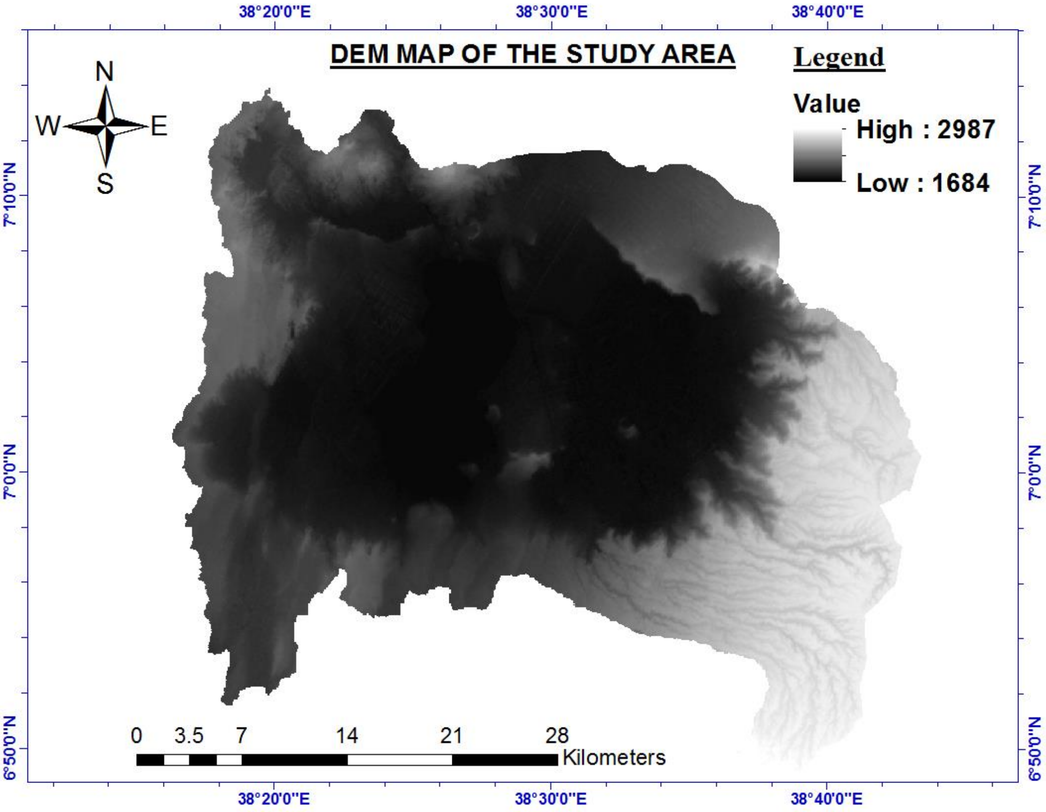

Figure 7. Digital Elevation Model of Hawassa Watershed

3.5.2. Soil data

Soil data is one of the major input data for the SWAT model with inclusive and chemical properties. The soil map of the study area was also obtained from the Ministry of Water Resources and Energy of Ethiopia. According to FAO/UNESCO – ISRIC classification, nine major soil groups were identified in the watershed of Hawassa (Figure 8).SWAT model requires soil physical and chemical properties such as soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type (appendix 3). These data were obtained from Ministry of Water Resources and Energy of Ethiopia as presented.

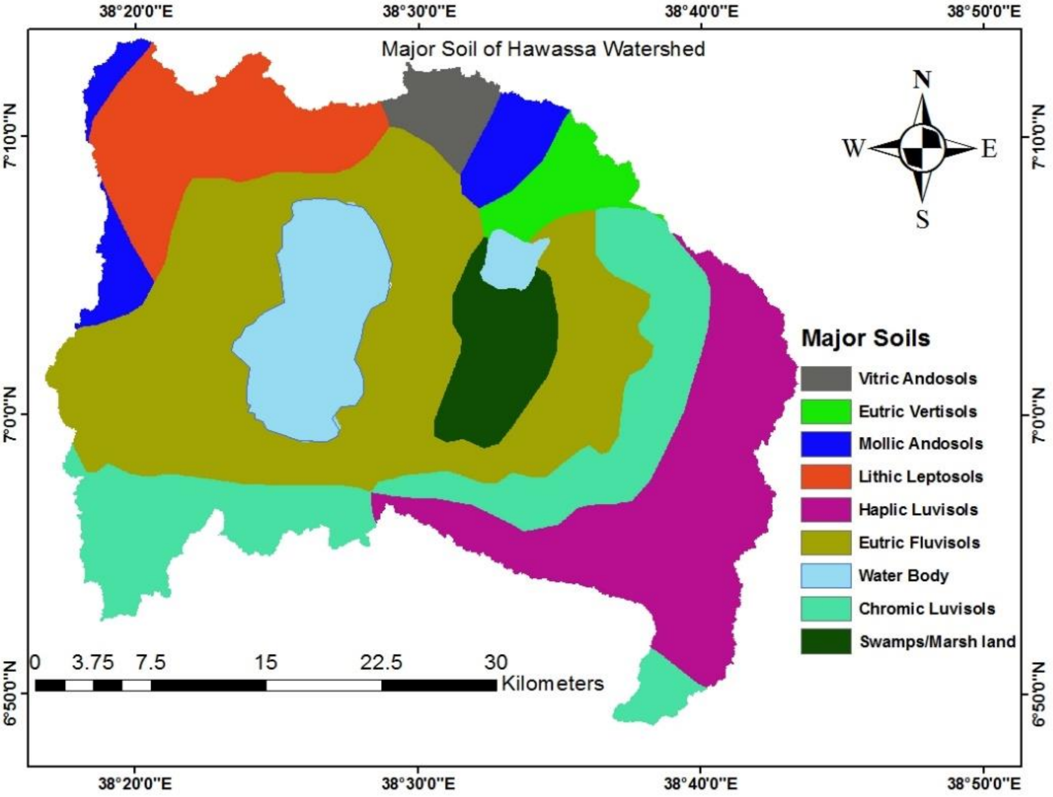

Figure 8. Soil Types of Hawassa Watershed (source: MoWR)

To integrate the soil map with SWAT model, a user soil database which contains textural and chemical properties of soils was prepared for each soil layers and added to the SWAT user soil databases using the data management append tool in ArcGIS. The symbol and areal coverage of the soil types are presented in Table 5.

Table 5. Soil Types of Hawassa Watershed and the areal coverage

Soil Type	Symbol	Area	
		ha	%
Chromic Luvisols	LVx	23296.7570	17.41
Eutric Fluvisols	FLe	53626.7819	40.08
Lithic Leptosols	LPq	13198.3644	9.87
Eutric Vertisols	VRe	4083.0457	3.05
Haplic Luvisols	LVh	22475.4350	16.80
Vitric Andosols	ANz	3194.7104	2.39
Water	Water	1376.9117	6.72
Mollic Andosols	ANm	5829.3103	4.36
Swamps	Swamps	6708.2437	5.01

3.5.3. Land Use Land Cover Data

Land use is one of the most important factors that affect runoff, evapotranspiration and surface erosion in a watershed. Land use is one of the highly influencing the hydrological properties of the watersheds. It is one of the main input data of the SWAT model to describe the Hydrological Response Units (HRUs) of the watersheds. The land use maps of the study area for 2011 year was classified by GIS software.

The SWAT model has predefined four-letter codes for each land use category (Table 6). These codes were used to link or associate the land use map of the study area to SWAT land use databases. Hence, while preparing the lookup-table, the land use types were made compatible with the input needs of the model.

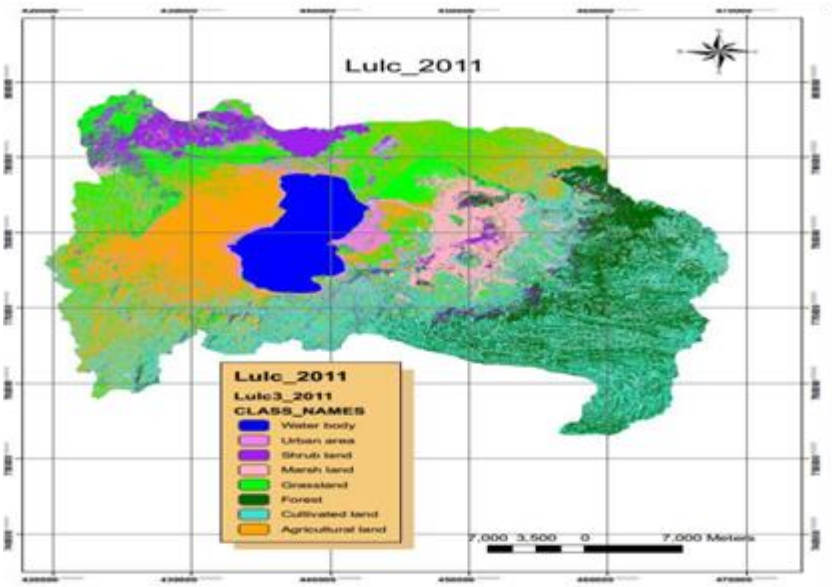

Figure 9. Land Use/ Cover Types of Hawassa Watershed

The reclassification of the land use map was made to represent the land use according to the specific LULC types and the respective crop parameter for SWAT database. A lookup table that identifies the SWAT land use code for the different categories of LULC were prepared to relate the grid values to SWAT LULC classes. The reclassifications of the LULC in SWAT database in Hawassa watershed were made according to the description shown below

Table 6. Land Use Classification and area of Hawassa Watershed as per SWAT Model

Land use / Land cover	Land use according to SWAT database	SWAT code	Area	
			ha	%
Intensively cultivated	Agricultural Land Generic	AGRL	84629.9396	63.26
Forest	Forest-Evergreen	FRSE	4207.6703	3.14
Water body	Water	WATR	7481.7563	5.59
Urban area	Residential	URBN	862.6902	0.64
Shrub land	Pasture	PAST	9999.4131	7.47
Grass land	Forest-Mixed	FRST	7984.9356	5.97
Swamps/ Marsh land	Wetlands-Non-Forested	WETN	7293.3992	5.45
Moderately cultivated	Spring Barley	BARL	11329.7556	8.47

3.5.4. Weather data

Weather data are among the main demanding input data for the SWAT simulation. The weather input data required for SWAT simulation includes daily data of precipitation, maximum and minimum temperature, relative humidity, wind speed, and solar radiation. These were obtained from the Ethiopian National Meteorological Agency. The weather data used were represented from five stations in and around Hawassa watershed, such as Hawassa, Haisawita, Shashemene, Yirbaduwancho, and Wondogenet stations. The first station i.e. Hawassa station is the first classes that have records on all climatic variables, whereas the other is the third class stations (Table 7). The climatic data used for this study covers 26 years from January 1990 to December 2015.

Based on the class of the stations, the number of weather variables collected varies from stations to stations that are grouped into two. The first group contains only rainfall data. The second group contains variables like maximum – minimum temperature, humidity, sunshine hours, and wind speed in addition to rainfall. However, missing values were identified in some of the climatic variables. The missed rainfall data were filled by normal ratio method. The other values were assigned with no data code (-99) which then filled by the weather generator embodied in the SWAT model from monthly weather generator parameters values. The monthly generator parameters values were estimated from the first weather station (Hawassa). Finally, the weather data were prepared in Text format with lookup tables as required by the model.

Table 7. Weather stations in and around the watersheds

No	Station Name	Latitude (deg)	Longitude (deg)	Rain fall	Max Temp	Min Temp	Relative Humidity	Wind Speed	Sunshine Hour
1	Hawassa	7.07	38.48	√	√	√	√	√	√
2	Haisawita	6.93	38.7	√	√	√			
3	Yirbaduwancho	6.92	38.02	√					
4	Wondo Genet	7.08	38.61	√					
5	Shashemene	7.20	38.60	√					

a) Filling missing rainfall data

Rainfall plays a central role in developing rainfall-runoff. Measured precipitation data are important to many problems in hydrologic analysis and design. For gages that require periodic observation, the failure of the observer to make the necessary visit to the gage may result in missing data. Vandalism of recording gages is another problem that results in incomplete data records, and instrument failure because of mechanical or electrical malfunctioning can result in missing data. Any such causes of instrument failure reduce the length and information content of the precipitation record.

A number of methods have for estimating missing rainfall data. There are station average method, normal ratio method, the quadrant method, and inverse-distance weighting method and regression methods. From five methods, normal ratio is used for this study. In the normal ratio method, the rainfall PA at station A is estimated as a function of the normal monthly or annual rainfall of the station under question and those of the neighboring stations for the period of missing data at the station under question.Missing records of the rainfall stations were estimated by using normal ratio method which is recommended to estimate missing data in regions where annual rainfall among stations differ by more than 10% (Dingman, 2002). This approach enables estimation of missing rainfall data by weighting the observation at N gauges by their respective annual average rainfall values as expressed by the equation 3.9 below.

$$P_X = \frac{N_X}{M}\left(\frac{P_1}{N_1} + \frac{P_2}{N_2} + \cdots + \frac{P_m}{N_m}\right) \qquad (Eq. 3.9)$$

Where: Px = the missing precipitation record, P1, P2… Pm = Precipitation records at the neighboring stations, M = Number of neighboring stations, Nx = Annual-average precipitation at the gage with missing values, N1, N2… Nm = Annual average precipitation at neighboring gauges

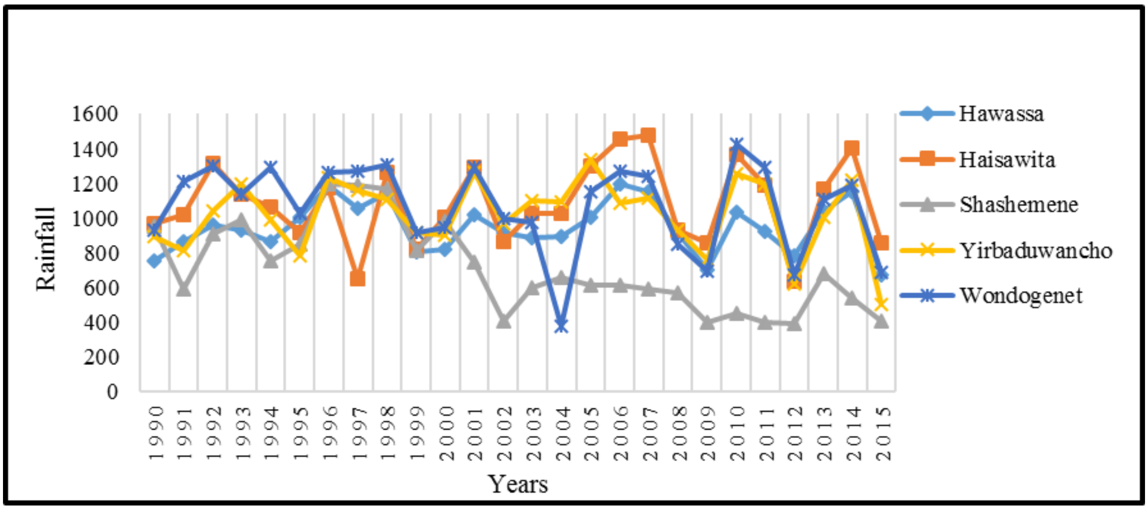

Figure 10. Long-term mean annual rainfall from a period of (1990-2015)

b) Checking the consistency of data

A consistent record is one where the characteristics of the record have not changed with time. Adjusting for gage consistency involves the estimation of an effect rather than a missing value. An inconsistent record may result from any one of a number of events; specifically, an adjustment may be necessary due to changes in observation procedures, changes in exposure of the gage, changes in land use that make it unreasonable to maintain the gage at the old location, and where vandalism frequently occurs.

Double-mass-curve analysis is the method that is used to check for inconsistency in a gage record. The curve is a plot on arithmetic graph paper, of cumulative rainfall collected at a gauge where measurement condition may have changed significantly against the average of the cumulative rainfall for the same period of record collected at several gauges in the same region.

The method for checking the consistency of a hydrological or meteorological record is considered an essential tool is for taking it for analysis purposes. It is determined by plotting the cumulative values of observed time series of the station for which consistency need to be checked on y-coordinate versus the cumulative value of observed time series of a group of a station on the x-axis, a break in slope of the curve would indicate that conditions have changed that location. The data series, which is inconsistency, is adjusted to consistent values by proportionality. Therefore, the station has to be adjusted for consistency of the record using equation. For this research Double- mass curve analysis and RAINBOW software were used to adjust inconsistent gage data.

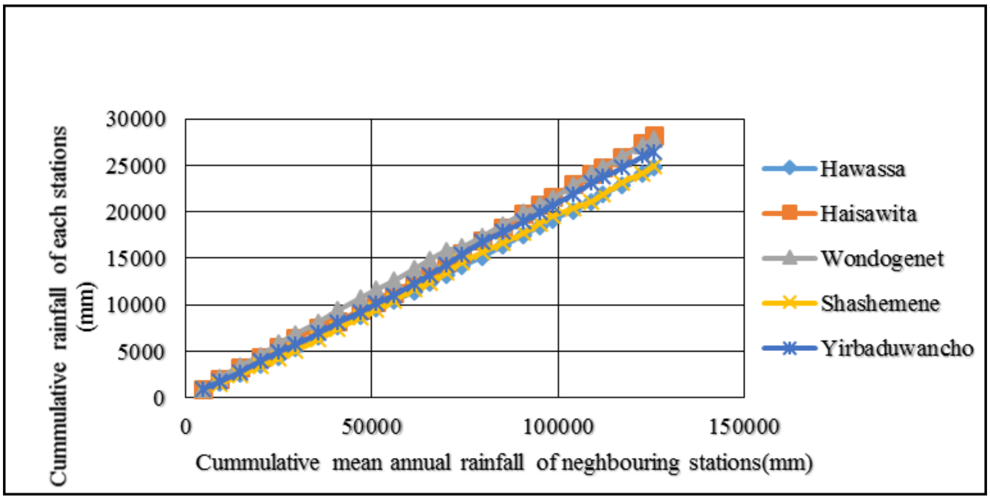

Figure 11. Double mass curve plot made for five stations

3.5.5. Hydrological data

River TikurWuha is the only perennial river, which flows to the Lake Hawassa, TikurWuha River is gauged since 1981 and it has a drainage area of 706 Km2. The values of daily TikurWuha river discharge (from 1990-2015) were collected from the Hydrology Department of the Ministry of Water Resources and Energy of Ethiopia. The daily river discharges of gauging station were used for model calibration and validation.

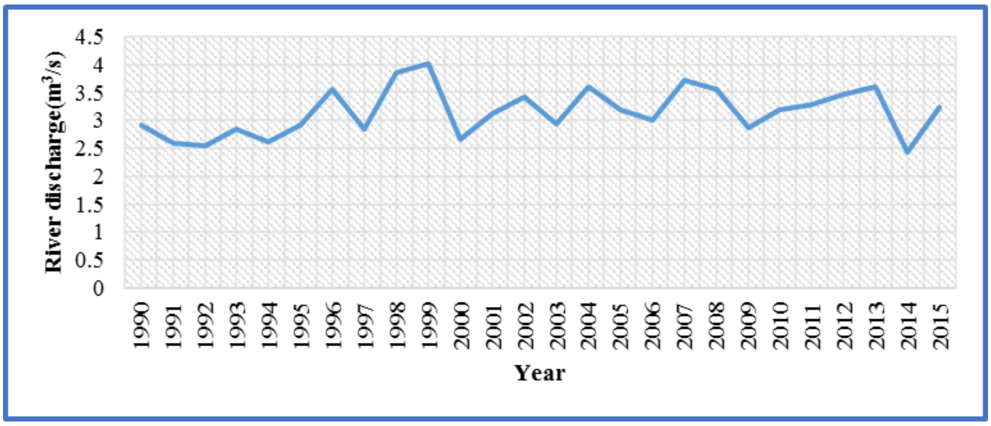

Figure 12. Long-term mean yearly river discharge of TikurWuha (1990-2015)

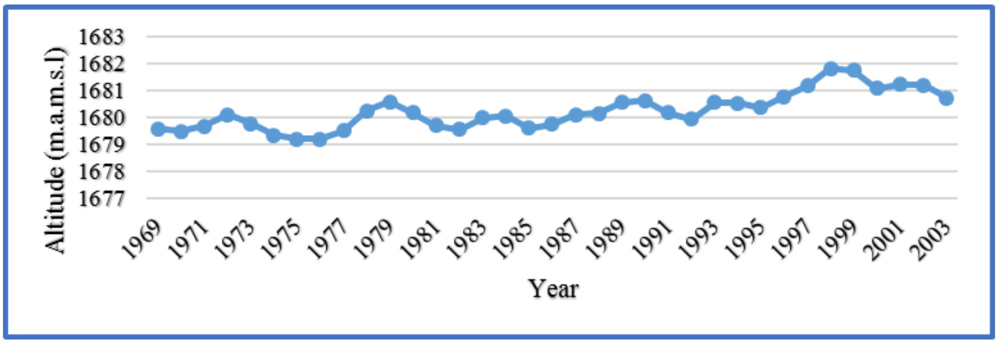

Figure 13. Hawassa lake level fluctuations (1969-2003). Source; Gebreegziabher, (2003)

3.6. Model Parameters Transfer Method

Three methods namely spatial proximity, global averages, and regression were used in determining the parameter sets to be transferred from the gauged sub-watersheds to the ungauged sub-watersheds. The results of these three methods were analyzed statistically and compared to determine the best method.

3.6.1. Spatial proximity

According to this method, catchments that are geographically close to each other are expected to have similar behavior. The whole set of calibrated parameter values were transferred between sub-watersheds that are near each other. The underlying assumption here is that neighboring sub-watersheds should behave similarly because of similar climatic and physical characteristics. The donor sub-watersheds were calibrated and the changes applied to the various parameters were applied to the receiver sub-watersheds. The model was then run and the simulated streamflow was then compared to the observed streamflow of the receiver sub-watershed.

3.6.2. Global averages

The global average parameters were determined by computing the average of the values of each of the parameters attained during calibration, across all the sub-watersheds, therefore obtaining a single value for each of the parameters. The values were then written in the input file of the ungauged subwatershed. The model was then run using the parameter values obtained through the global average. The simulated streamflow was then compared to the observed streamflow of the test sub-watershed.

3.6.3. Regression method

Stepwise regression was used to determine functional relationships between sub watershed characteristics and model calibration parameters. Where relationships obtained were significant, resulting equations were used to compute model parameters for each of the ungauged sub-watersheds.

3.7. Model Setup

3.7.1. Watershed Delineation

Lake Hawassa watershed is a closed basin, which has no specific outlet. The only gauged area is Tikurwuha subwatershed. The model setup was done for both gauged watershed as well as for the whole watershed area. After calibration and validation of the model at Dato village station, parameter transfer method (spatial proximity) was used to find water balance components for the whole Hawassa watershed.

The watershed and subwatershed delineation of Hawassa was performed using 20 m resolution DEM data using Arc SWAT model watershed delineation function. First, the SWAT project set up was created. The watershed delineation process consists of five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub-basin parameters. Once, the DEM setup was completed and the location of the outlet was specified on the DEM, the model automatically calculates the flow direction and flow accumulation. Subsequently, stream networks, sub-watersheds and topographic parameters were calculated using the respective tools.

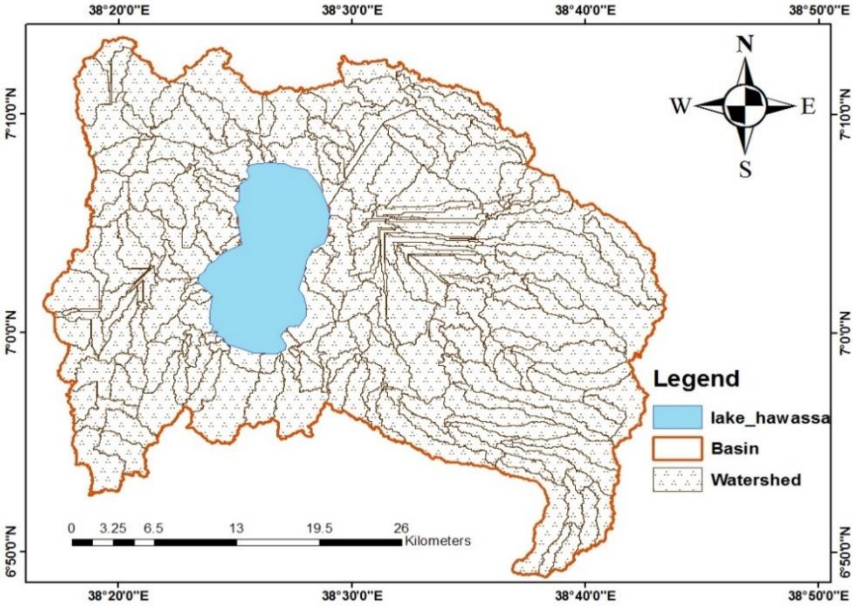

Figure 14. Sub Watersheds Map of the Lake Hawassa Watershed

The stream definition and the size of sub-basins were carefully determined by selecting a threshold area or minimum drainage area required to form the origin of the streams. Using a threshold value suggested by the Arc SWAT interface, the Hawassa watershed was delineated into 216 sub-watersheds having an estimated total area of 1300km^2 (Figure14). However, the total area of the watershed as obtained from the Minister of Water Resources

(MoWR) was estimated to be 1400 km^2. There is a slight deviation between the delineated and that obtained from the MoWR database. The difference in the total area between the delineated and the database may be due to the lake area, which was cut and removed from the DEM, and the area was taken as the outlet. In addition, it may be due to the difference in the DEM resolution or the watershed delineator model used.

Table 8. The slope classes of the Lake Hawassa watershed

Classes	Slope range (%)	Area	
		ha	%
Class 1	0-6	26513.8718	19.82
Class 2	6-20	67077.4761	50.14
Class 3	>20	40198.2121	30.05

During the watershed delineation process, the topographic parameters (elevation, slope) of the watershed and its subwatershed were also generated from the DEM data. Accordingly, the elevation of the watershed ranges from 1624 to 2968 above mean sea level, the highest elevation is around Wondogenet and the lowest at the Hawassa Lake i.e. watershed outlet. Slope classification was carried out based on the height range of the DEM used during watershed delineation. The slope values of the watershed were reclassified in percent. It was reclassified into three classes (Table 8).

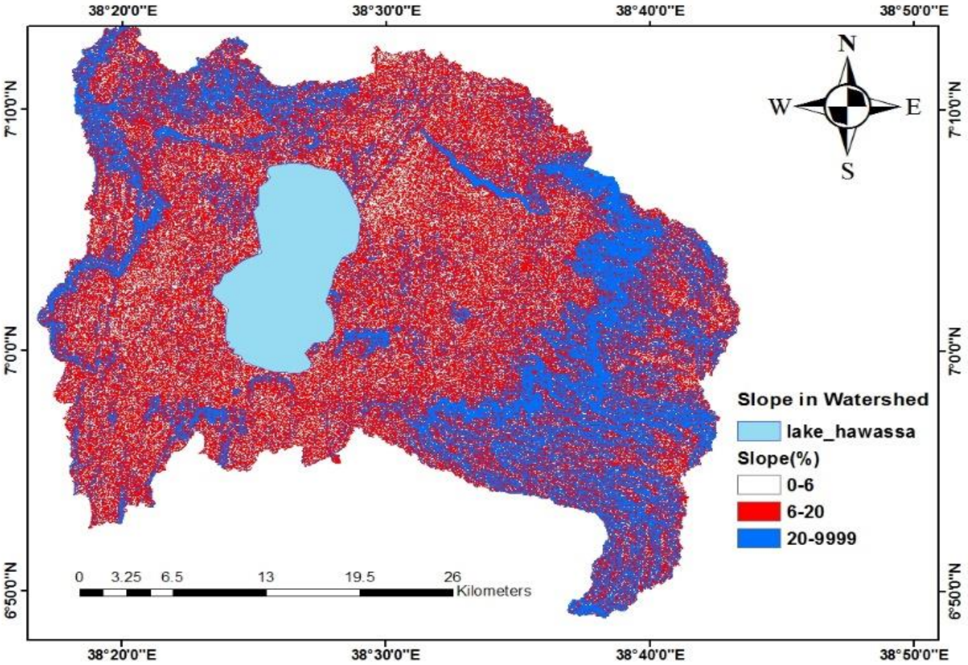

Figure 15. Slope in Lake Hawassa watershed

3.7.2. Hydrologic response units analysis

The sub-watersheds were divided into HRUs by assigning the threshold values of land use and land cover, soil and slope percentage. In general, the threshold level used to eliminate minor land use and land covers in sub-basin, minor soil within a land use and land cover area and minor slope classes within a soil on specific land use and land cover area. Following minor elimination, the area of remaining land use and land covers, soils and slope classes are reapportioned so that 100 % of their respective areas are modeled by SWAT. Land use, soil and slope characterization for the watershed were performed using commands from the HRU analysis menu on the Arc SWAT Toolbar. These tools allowed loading land use and soil maps, which are in raster format into the current project, evaluate slope characteristics and determining the land use/soil/slope class combinations in the delineated sub-watersheds.

In the model, there are two options in defining HRU distribution: assign a single HRU to each subwatershed or assign multiple HRUs to each subwatershed based on a certain threshold value. The SWAT user's manual suggests that a 20 % land use threshold, 10 % soil threshold and 20 % slope threshold are adequate for the most modeling application. Therefore, for this study, HRU definition with multiple options that accounts for 20% land use, 10% soil and 20% slope threshold combination was used. These threshold values indicate that land uses, which form at least 20% of the subwatershed area, and soils, which form at least 10% of the area within each of the selected land uses will be considered in HRU.

Hence, the Lake Hawassa watershed was divided into 706 HRUs, each has a unique land use and soil combinations. The number of the HRUs varies within the sub-watersheds.

3.7.3. Weather generator

In developing countries, there is a lack of a full and realistic long period of climatic data. Therefore, the weather generator solves this problem by generating data from the observed one (Danuso, 2002). The Model requires the daily values of all climatic variables from measured data or generated from values using monthly average data over a number of years. This study used measured data for all climatic variables. However, the weather data obtained for the stations in and around Hawassa watershed had missed records in some of the variables. Therefore, these missed values were filled with the weather generator utility in the Arc SWAT Model from the values of weather generator parameters (appendix 2). Weather data of Hawassa stations with continuous records were used as an input to determine the values of the weather generator parameters. Hence, for weather generator data definition, the weather generator data file wgnstations.txt was selected first. Subsequently, rainfall data, temperature data, relative humidity data, solar radiation data, and wind speed data were selected and added to the model.

To generate the data, weather parameters were developed by using the weather parameter calculator PCPSTATA and dew point temperature calculator DEW02, which were downloaded from the SWAT website. Average Daily Dew Point Temperature was calculated using the Dew point calculator (Dew02) from daily maximum temperature, daily minimum temperature, and average relative humidity. Moreover, daily solar radiation was calculated from the daily available sunshine hour’s data.

3.7.4. Sensitivity analysis

Calibration is necessary to optimize the values of the model parameters, which help to reduce the uncertainty in the model outputs. However, such type of model with multiple parameters, the difficult task is to determine which parameters are to be calibrated. In this case, sensitivity analysis is important to identify and rank parameters that have a significant impact on the specific model outputs of interest (Van Griensven et al., 2006). Therefore, for this study, a sensitivity analysis was done prior to the calibration process in order to identify important parameters for model calibration. The average monthly streamflow data of 6 years from 2005 to 2010 of the watershed gauging station were used to compute the sensitivity of the stream flow parameters.

In the sensitivity process, by entering the Arc SWAT interface sensitivity analysis window, first, the SWAT simulation was specified for performing the sensitivity analysis and the location of the Subbasin where observed data was compared against simulated output. Then, selected parameters were entered for the sensitivity analysis with the default lower and upper parameter bounds. Hence, 14 flow parameters were included for the analysis with default values as recommended by (Van Griensven et al., 2006).

3.7.5. Model calibration and validation

Following the sensitivity analysis result, model calibration was done to obtain optimum values for sensitive parameters. SWAT provides three options for calibration: auto-calibration, manual calibration, and a combination of these two methods. For this study, the auto-calibration procedure was used. The calibration was done on monthly time steps using the average measured streamflow data of the Tikurwuha watershed covering from January 2005 to December 2010. In this research, sensitivity analysis of the model, calibration, and validation has been done using the SWAT-CUP (SWAT Calibration Utility Program) tool.

Eawag Swiss Federal Institute, to analyze the prediction uncertainty of SWAT model calibration and validation results, developed SWAT- CUP. It provides the user to make a choice between a number of algorithms to perform the calibration such as SUFI2 (Sequential Uncertainty Fitting ver.2), GLUE (Generalized Likelihood Uncertainty Estimation), MCMC (Markov Chain Monte Carlo), ParaSol (Parameter Solution). In this study SUFI2.and has been used as the calibration algorithm since it has been a widely used popular calibration tool and has achieved good calibration and uncertainty results. In SUFI2, the uncertainty in parameters portrays all sources of uncertainties like uncertainty in parameters, conceptual model, driving variables (e.g., rainfall) and measured data.

Several iterations of 500 simulations each were carried out for the calibration period of 2005-2010 for monthly flows by adjusting the sensitive parameters obtained through sensitivity analysis until the shapes of predicted and measured stream flows were found to be in reasonable agreement and the criteria of objective functions are satisfied.

Validation was also done to compare the model outputs with an independent data set without making a further adjustment of the parameter values. Model validation is a comparison of the model outputs with an independent data set without making a further adjustment, which may adjust during the calibration process. The measured data of average monthly streamflow data of 5 years from January 2011 to December 2015 were used for the model validation process. In this process, the two model performance values were also checked here to make sure that the simulated values are still within the accurate limits.

Abbreviations used in SWAT-CUP are ;95PPU: 95 Percent Prediction Uncertainty, This value is calculated for the 2.5% and 97.5% levels of an output variable, and 5% of the very bad simulations are disallowed, Objective Function: Nash-Sutcliffe efficiency (NSE), Coefficient of determination (R^2), Root Mean Square Error (RMSE) ,P-factor: It represents the percentage of observations, which comes under the 95PPU, R-factor: Represents the relative width of 95% probability band, T-Stat: Provides a measure of sensitivity, larger absolute values are considered to have higher sensitivity, P-Value: Determination of the significance of sensitivity, A-value is more significant if it is close to zero. A simulation in which P-factor is one and R-factor is zero exactly corresponds to measured data.

3.8. Model Performance Evaluation

To evaluate the model simulation outputs in relative to the observed data, model performance evaluation is necessary. There are various methods to evaluate the model performance during the calibration and validation periods. For this study, two methods were used: coefficient of determination (R^2), and Nash Sutcliffe simulation efficiency (NSE). The performance of the model is acceptable and is considered satisfactory when the coefficient of determination $R^2 \geq 0.65$, Nash Sutcliffe efficiency NSE ≥ 0.5 and PBIAS lies between -20 to +20 (Moriasi et al., 2007).

The coefficient of determination (R^2):

It is a value that depicts how well a data fits into a statistical model. The range of coefficient of determination lies between zero and one. When R^2 is, one it can be depicted that the regression line perfectly fits the data, while an R^2 is zero indicates that the line does not fit the data at all equation 3.10.

$$R^2 = \frac{[\sum_{i=1}^{n}(Q_{si} - Q_{sm})(Q_{oi} - Q_{om})]^2}{\sum_{i=1}^{n}(Q_{si} - Q_{sm})^2 \sum_{i=1}^{n}(Q_{oi} - Q_{om})^2} \qquad \text{(Eq.3.10)}$$

Where Qsi is the simulated value, Qoi is the measured value, Qom is the average observed value and Qsm is the average simulated value.

Nash Sutcliffe efficiency (NSE)

The Nash–Sutcliffe model efficiency coefficient is used to depict the predictive power of hydrological models. The Nash-Sutcliffe efficiency has a range between -∞ to one. When efficiency is equal to one it indicates a perfect match of estimated discharge with the observed data whereas an efficiency of zero suggests that the predictions of model are as accurate as the observed data’s mean, while an efficiency, which is less than zero (E < 0), corresponds that the observed mean is a better predictor than the model equation 3.11.

$$NSE = 1 - \frac{\sum_i (Q_{oi} - Q_{si})^2}{\sum_i (Q_{oi} - \overline{Q_{om}})^2} \qquad (Eq. 3.11)$$

Where; Q_{oi} is observed, Qsi is the simulated and Qom is the observed average values.

Percentage bias (PBIAS):

It is the deviation of simulated data from observed data being evaluated, which is expressed as a percentage. The low magnitude values indicate accurate simulation of the model.

Table 9. General performance ratings for recommended statistics of flow. Source; Moriasi et al. (2007).

Performance Rating	NSE	R^2
Very Good	$0.7 < NSE < 1.00$	$0.75 < R^2 < 1.00$
Good	$0.6 < NSE < 0.7$	$0.65 < R^2 < 0.75$
Satisfactory	$0.50 < NSE < 0.6$	$0.50 < R^2 < 0.65$
Unsatisfactory	$NSE < 0.50$	$R^2 < 0.50$

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1. Watershed Delineations

From a minimum user-defined threshold area of 65009 ha, 216 sub-basins were delineated in the Lake Hawassa watershed area of 1300 km^2 as it is outlined in Figure 16. Each sub-basin boundary marks the end of reach, the end point of which the accumulation point for all flow from upstream which is then fed into downstream sub-basin and reach. Once the main reach and the longest paths/tributaries are formed, the model uses other physical parameters (soil, land use and land slope) to define HRUs.

From the assumed threshold values for HRU delineation, we have found 706 HRUs in 216 sub-basins. Each HRU is composed of land use, soil type, and slope parameters.

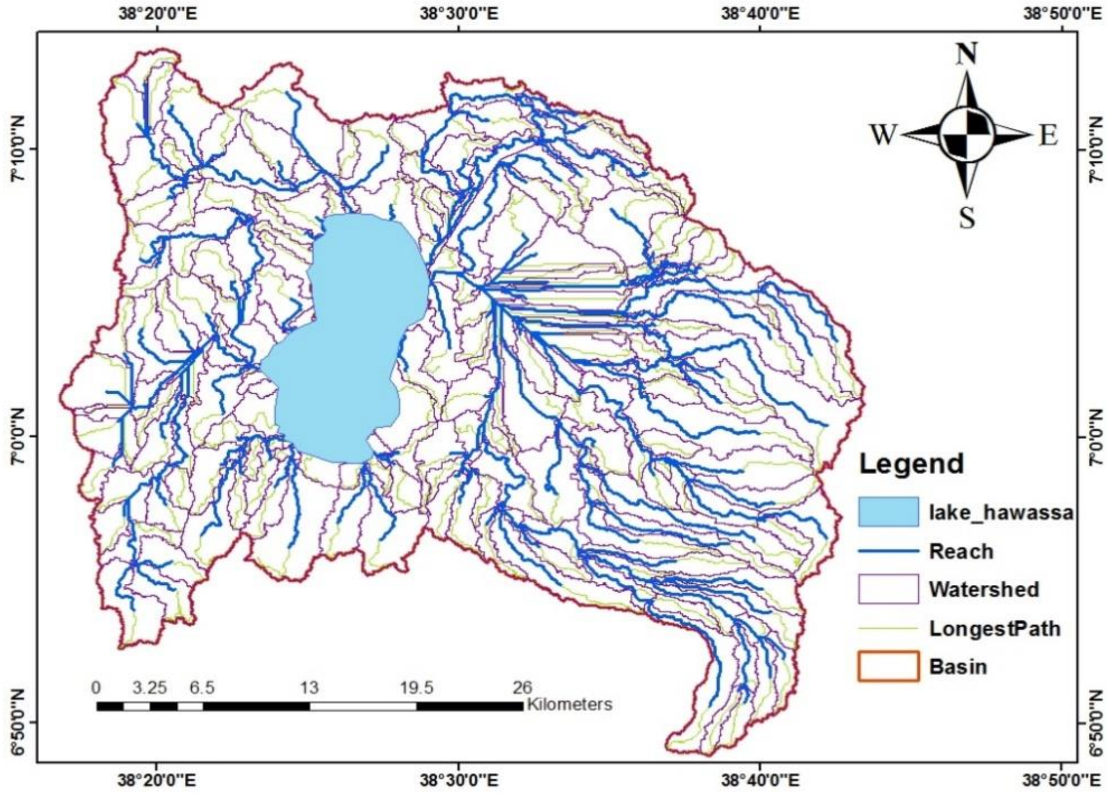

Figure 16. Sub-basin delineation in the Lake Hawassa watershed by SWAT model

4.2. Stream Flow Modeling

4.2.1. Sensitivity analysis of Tikurwuha subwatershed

Sensitivity analysis was performed on flow parameters of SWAT on monthly time steps with observed data of the Tikurwuha River gauge station. For this analysis, 14 parameters were considered and only 10 parameters were identified to have significant influence in controlling the stream flow in the watershed. Table10 presents parameters that resulting greater relative mean sensitivity values for monthly stream flow.

Table 10. List of Parameters and their ranking values for monthly flow

Parameters		Lower and Upper bound	Rank
Name	Description		
ALPHA_BF	Base flow alpha factor (days)	0-1	10
CN2	SCS runoff curve number (%)	- 25 to +25	2
ESCO	Soil evaporation compensation factor	0-1	7
CH_N2	Manning's roughness coefficient	0-1	8
RCHRG_DP	Deep aquifer percolation fraction	0 - 1	9
GWQMN	Threshold depth of water in the shallow aquifer required for return flow (mm)	0-1000	6
ALPHA_BNK	Base flow alpha factor for bank storage	0-1	5
SOL_AWC	Soil available water capacity (water/mm soil)	-25 to +25	3
SOL_K	Saturated hydraulic conductivity(mm/hour)	0 to 2000	1
GW_REVAP	Groundwater "revap" coefficient	0.02 -0.2	4

The result of the sensitivity analysis indicated that these 10 flow parameters are sensitive to the SWAT model i.e. the hydrological process of the study watershed mainly depends on the action of these parameters. Saturated hydraulic conductivity (mm/hour) (SOL_K), Curve number (CN2), soil available water capacity (SOL_AWC), Groundwater "revap" coefficient (GW_REVAP), Base flow alpha factor for bank storage (ALPHA_BNK) are identified to be highly sensitive parameters and retained rank 1 to 5, respectively. The other parameters such as, threshold depth of water in the shallow aquifer required for return flow (GWQMN), Soil evaporation compensation factor (ESCO), Manning's roughness coefficient (CH_N2), Deep aquifer percolation fraction (RCHRG_DP) and Alpha factor (ALPHA_BF) are identified as slightly important parameters that were retained rank 6 to 10, respectively. The remaining parameters (4 parameters) were not considered during the calibration process, as the model simulation result was not sensitive to these parameters in the watershed.

4.2.2. Calibration and validation of the model for Tikurwuha subwatershed

The simulation of the model with the default value of parameters in the Tikurwuha sub watershed showed relatively weak matching between the simulated and observed streamflow hydrographs. Hence, calibration was done for sensitive flow parameters of SWAT with observed average monthly streamflow data. First, some sensitivity flow parameters were adjusted by the manual procedure based on the available information in the literature. Then, auto calibration was run using sensitive parameters that were identified during sensitivity analysis.

Table 11. The result of calibrated flow parameters

Parameters		Lower and Upper bound	Fitted value
Name	Description		
ALPHA_BF	Base flow alpha factor (days)	0-1	-0.149674
CN2	SCS runoff curve number (%)	- 25 to +25	0.012266
ESCO	Soil evaporation compensation factor	0-1	0.067568
CH_N2	Manning's roughness coefficient	0-1	0.179275
RCHRG_DP	Deep aquifer percolation fraction	0 - 1	2.996349
GWQMN	Threshold depth of water in the shallow aquifer required for return flow (mm)	0-1000	12.892766
ALPHA_BNK	Base flow alpha factor for bank storage	0-1	-0.364493
SOL_AWC	Soil available water capacity (water/mm soil)	-25 to +25	0.539980
SOL_K	Saturated hydraulic conductivity(mm/hour)	0 to 2000	-0.923168
GW_REVAP	Groundwater "revap" coefficient	0.02 -0.2	0.115262

During this step, the model was run for a period of 26 years from 1990 to 2015.The first two years was considered for the model warm-up period, and calibration was performed for 6 years from 2005 to 2010. The calibration result for monthly flow is shown in figure 17. The result of calibration for monthly flow showed that there is a good agreement between the measured and simulated average monthly flows with Nash-Sutcliffe simulation efficiency (NSE) of 0.66 and coefficient of determination (R^2) of 0.71 as shown in Table 12.

The model validation was also performed for 5 years from 2011 to 2015 without further adjustment of the calibrated parameters. The validation result for monthly flow is shown in figure 18. The validation showed a satisfactory agreement between the simulated and measured monthly flow with the NSE value of 0.59 and R^2 of 0.64 as shown in Table 12.

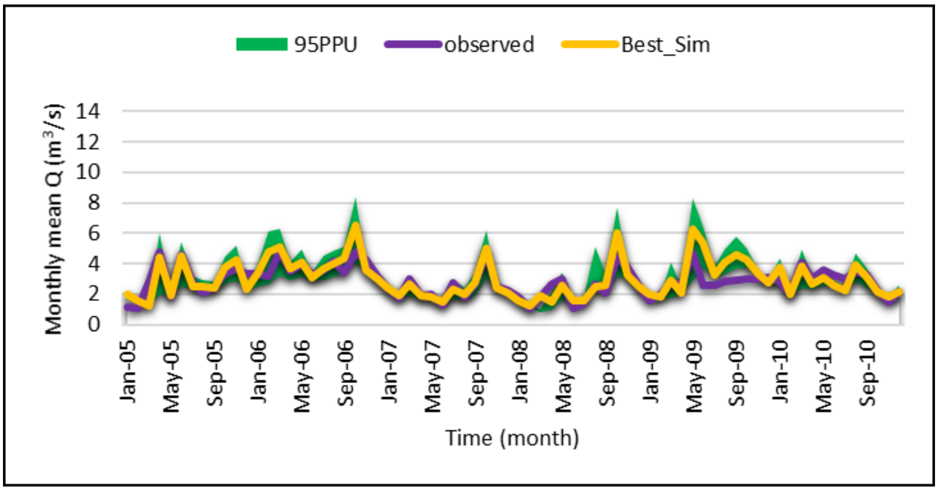

Figure 17. The result of calibration for average monthly stream flows

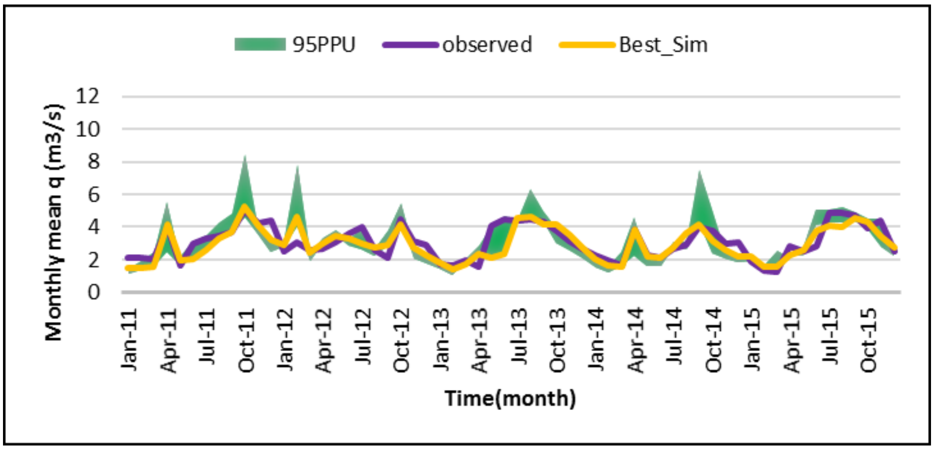

Figure 18. The result of Validation for average monthly stream flows

The measured and simulated average monthly flow for Tikurwuha subwatershed was obtained. During the calibration period, they were 3.04 and 2.98 m^3/s, respectively. The measured and simulated average monthly flow for the validation period was 3.07 and 2.93 m^3/s, respectively. These indicate that there is a reasonable agreement between the measured and the simulated values in both calibration and validation periods (Table 12).

Table 12. Comparison of Measured and simulated monthly flow

Period	Average monthly flow (m^3/s)		NSE	R^2
	Measured	Simulated		
Calibration (2005-2010) Period	3.04	2.98	0.66	0.71
Validation (2011 - 2015) Period	3.07	2.93	0.59	0.64

As can be indicated in Table 12, the model performance values for the calibration and validation of the flow simulations are good and satisfactory respectively. This indicates that the model adequately captured the physical processes involved in the generation of streamflow in the watershed. Hence, the model simulations can be used for various water resource management and development aspects.

The following figures showed that the values of the scatter plots of the measured and simulated monthly flows data for the calibration and validation periods. There is a fire linear correlation between the two datasets (measured and simulated).

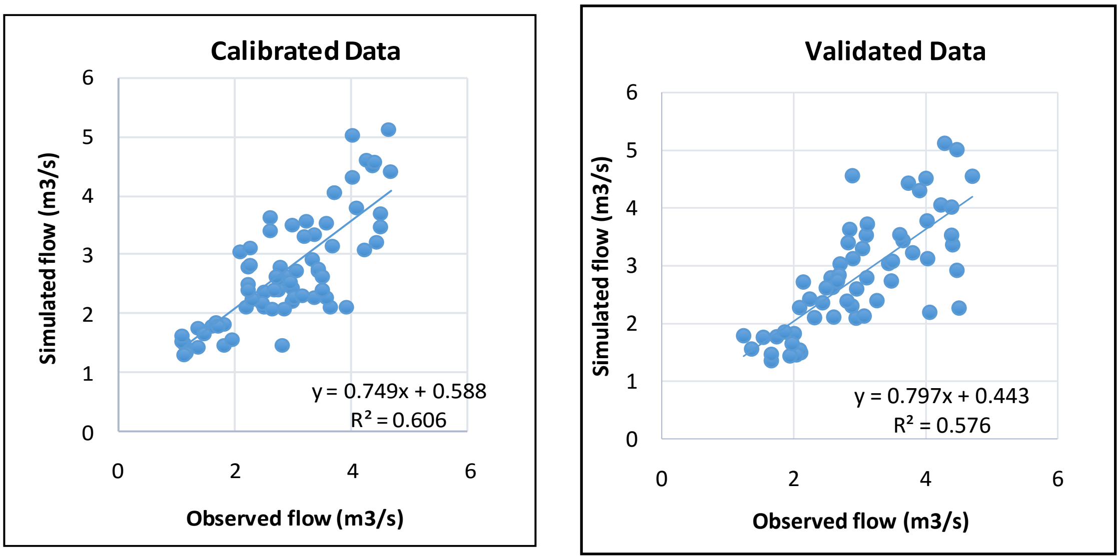

Figure 19. Scatter plots of the calibration and validation periods.

In general, the Model performance assessment indicated that there are a good correlation and agreement between the monthly measured and simulated flows.

4.3. Model Parameters Regionalization

Calibration at gauged Tikurwuha catchment is a prerequisite for regionalization of model parameters. To this end, the SWAT model is calibrated against a 6-year discharge record (2005-2010) and validated on five other years (2011-2015) for the catchments. The adjustment between the observed and simulated river flow has been achieved by tuning 10 SWAT model parameters identified as the most sensitive on the study area.

4.3.1. Gauged and un-gauged watersheds similarities

The sub-watersheds in Hawassa watershed with similar land cover, soil type, and slope range are identified and the results are presented in Table 13. Un-gauged sub-watersheds in Hawassa are similar to gauged sub-watersheds of Tikurwuha sites.

Table 13. Characteristics of watersheds above the gauged and un-gauged sites

Gauged sub-watersheds	Un-gauged sub-watersheds
1.Tikurwuha sub watershed	1.Un-gauged sub watershed in Hawassa
Land cover /use	Land cover /use
mixed cropping shrub grasslands	mixed cropping shrub grasslands
Soil type	Soil type
Eutric Vertisols Mollic Andosols	Eutric Vertisols Mollic Andosols
Slope range	Slope range
0 - 6% 6- 20% (dominant) >20 %	0 - 6% 6- 20% (dominant) >20 %

4.3.2. Parameter transfer for streamflow simulation at un-gauged sub watersheds spatial proximity

Spatial proximity approach was carried out by transferring parameters from a neighboring donor sub-watershed to the receiver sub-watershed (Heuvelmans *et al*., 2004;). The parameters in Table 11, which are calibrated for Tikurwuha subwatershed, were written back to original Arc swat project of Lake Hawassa watershed. The model was then run using the parameter values obtained from calibration. The rationale was that because the sub-watersheds are near each other, they have similar behavioral characteristics. This is because watershed and climatic conditions vary evenly in space (Oudin *et al*., 2008).

4.4. Monthly and Average Annual Water Balance Components of the Watershed

The annual average basin values presented in the Table below. The average annual precipitation was 1004.6 mm. This precipitation apportioned to water balance components in which water yield has accounted high followed by actual evapotranspiration (499.2mm) and Percolation out of the soil. Surface runoff and deep aquifer recharge contributed less to the flow. The average annual ET of the basin is around 50% of the precipitation.

Table 14. Average Annual water balance components of the basin

Water Balance Components	Average annual values(mm)
Precipitation	1004.6
Surface runoff	91.06
Lateral flow through soil	135.82
Groundwater (shallow aquifer)	260.07
Deep aquifer recharge	64.94
Total water yield	551.9
Percolation out of soil	325.01
Actual Evapotranspiration	499.2
Total Recharge	325.01
Revap	0.45
Trans. Loss	0

Average annual water balance simulated for a base period of 1990 through 2015 in sub-basins and its variability across the watershed is as displayed in the figure below.

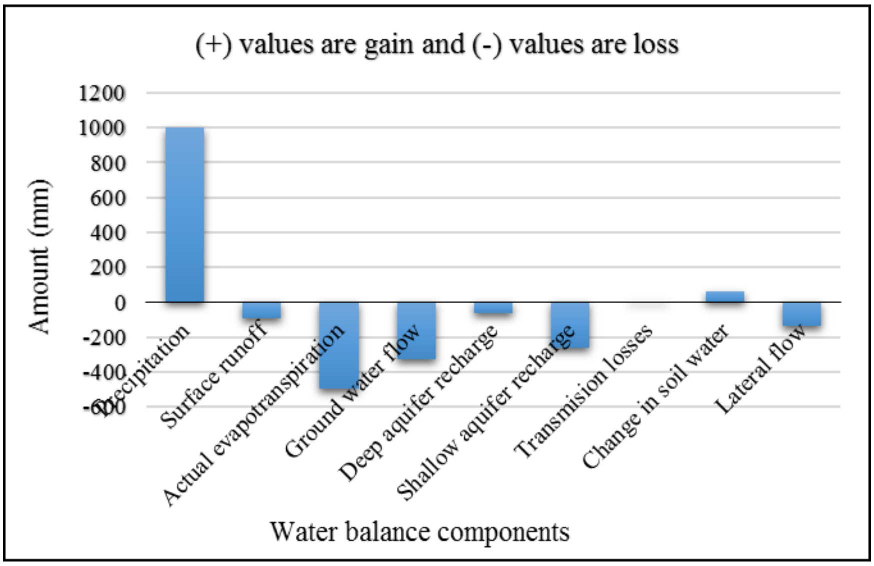

Figure 20. Average annual water balances for Lake Hawassa watershed.

The monthly basin values were presented in Table 15. The hydrological parameters such as water yield, surface flow, groundwater flow indicated a good relationship with precipitation. Generally, water yield was more from July to October in a year.

The model simulated surface runoff using curve number technique and lateral flow through soil by storage routing technique. Whenever there is rainfall, surface runoff and lateral flow have contributed to the stream flow. The maximum amount of surface runoff simulated was 13.8 mm in the month of August that coincided with the highest amount of rainfall recorded during the month. Soil moisture values varied from 51.58mm to 78.51 mm.

Table 15. Average Monthly water balance of the Basin

Mon (mm)	Rainfall (mm)	Surface runoff (mm)	Lateral flow (mm)	Water Yield (mm)	ET (mm)	PET (mm)
Jan	29.82	2.76	3.88	17.05	22.16	114.38
Feb	31.06	2.84	3.94	15.77	22.61	114.42
Mar	83.63	4.88	10.53	28.55	46.31	127
Apr	117.97	8.96	15.6	47.63	57.51	113.12
May	122.81	9.6	16.85	61.96	59.88	111.81
Jun	98.9	9.52	13.11	55.11	47.88	96.15
Jul	121.88	13.71	16.36	63.24	49.39	88.18
Aug	128.82	13.8	17.91	70.82	52.04	94.12
Sep	125.99	10.45	17.45	70.75	53.42	97.53
Oct	82.27	7.66	12.13	61.95	41.32	106.97
Nov	36.5	3.98	5.09	36.98	25.73	105.42
Dec	24.7	2.87	2.95	21.93	20.78	110.58

4.5. Annual Balance of Blue and Green Water Resource.

Annual and monthly blue water flow, green water flow, and green water storage was estimated using the calibrated model. Furthermore, annual and monthly water resources for different HRU will be aggregated to estimate water resources available at the river catchment and city/region scales (Dulce et al., 2014). All water balance components calculated for each sub catchments are listed in appendix 1. Annual average values for the various hydrological components, obtained by aggregating simulated results over the period 1990-2015, were used to quantify Blue and Green water general balance as shown in Table 16 and figure 21.

Table 16. Average simulated (mm yr^{-1}) from (1992-2015) water resource components

YEAR	PRECIP (mm)	PET (mm)	Green water flow (mm)	Green water storage (mm)	PERC (mm)	SURQ (mm)	GW_Q (mm)	WYLD (mm)	LAT_Q (mm)	DA_RCHG (mm)	Blue water (mm)
1992	1068.82	1246.69	525.80	79.14	347.45	75.09	272.52	572.85	157.20	68.91	641.75
1993	998.23	1190.28	491.23	73.96	332.26	69.63	272.49	558.07	147.92	68.45	626.52
1994	963.12	1232.77	429.33	55.74	336.73	95.61	271.72	582.78	147.61	68.43	651.21
1995	988.65	1256.18	448.92	53.74	324.08	103.28	248.74	558.60	144.47	62.87	621.47
1996	1201.24	1241.60	513.67	73.91	422.05	126.49	347.81	740.61	179.46	87.12	827.73
1997	1047.13	1283.71	518.27	78.13	330.53	78.97	248.96	544.53	154.43	63.39	607.91
1998	1194.12	1238.04	492.49	54.10	430.57	125.54	355.76	753.11	182.98	88.80	841.91
1999	830.40	1268.89	444.44	58.15	257.23	55.08	206.66	434.53	121.20	51.90	486.44
2000	876.97	1368.45	451.79	39.52	261.70	99.11	209.16	480.15	119.66	52.71	532.86
2001	1121.26	1336.07	540.33	62.90	372.55	83.06	299.94	624.90	167.01	75.52	700.42
2002	915.96	1112.06	436.75	61.56	288.49	84.97	221.56	495.68	133.83	56.10	551.78
2003	931.25	1274.09	478.07	63.22	287.14	85.88	232.30	508.20	132.02	58.72	566.92
2004	830.30	1281.86	433.85	50.58	251.31	78.63	207.92	450.53	112.07	51.73	502.26
2005	1072.52	1285.43	485.78	60.40	376.63	90.95	298.72	626.70	162.43	75.30	702.00
2006	1239.32	1230.33	519.72	69.36	435.26	128.28	341.66	741.75	186.52	86.31	828.07
2007	1205.61	1256.58	471.68	66.85	429.59	162.90	355.92	785.79	178.10	88.95	874.73
2008	912.89	1269.26	425.30	60.67	319.06	73.82	246.52	519.36	137.46	62.35	581.71
2009	725.73	1323.08	420.66	55.55	210.47	41.02	162.18	344.93	101.24	40.62	385.54
2010	1140.23	1234.38	486.58	78.51	406.36	106.69	327.14	695.99	180.47	82.48	778.47
2011	1018.49	1287.64	451.68	56.53	358.22	102.69	294.81	630.53	159.41	74.25	704.78
2012	743.09	1298.84	395.21	53.01	234.77	53.39	193.86	405.15	109.49	48.35	453.50
2013	1081.76	1251.29	479.61	53.52	370.29	112.39	294.34	638.81	158.60	74.12	712.94
2014	1186.23	1294.99	543.83	63.60	396.66	106.83	313.61	673.16	174.42	79.12	752.27
2015	703.47	1370.41	413.15	51.58	207.67	43.00	166.94	348.78	97.16	41.96	390.74
Average	999.87	1268.04	470.76	61.43	332.79	90.97	266.30	571.48	147.71	67.02	638.50

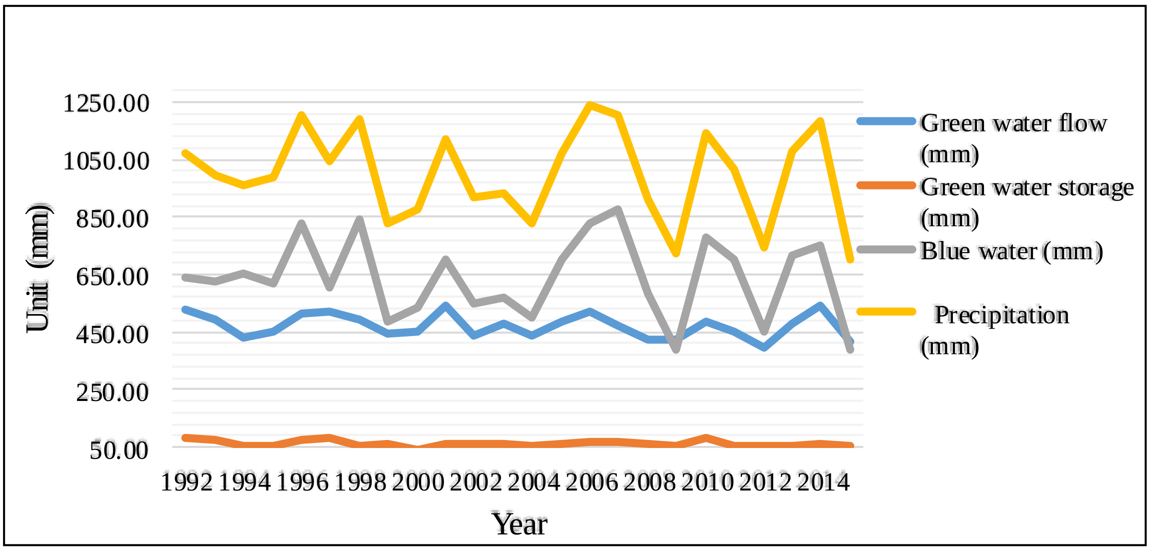

Figure 21. Long-term average annual values (mm yr−1) of different water resources.

4.5.1. Spatial and temporal blue water availability across the watershed

The spatiotemporal changes of blue and green water play an important role in water resource planning and management (Zuo et al., 2015). Hydrological components: Evapotranspiration (ET), Soil Water (SW), Water yield (WYLD), Groundwater Recharge (GW_RCHG) and Groundwater contribution to stream (GW_Q) obtained from the well-calibrated SWAT model was used for calculating blue and green water at monthly and annual timescales.

The spatial distribution of mean annual blue water, based on the simulated period (1990–2015) for Lake Hawassa watershed are shown in figure 22 below. The spatial distribution of blue water was found to be influenced by the rainfall pattern. The maximum precipitation was observed in upstream of the watershed and the annual blue water flow was found to be high in Wondo-Genet sub-catchment, where the amount of average blue water observed to be 1216 mm per year.

The minimum annual blue water was observed in the western area of Lake Hawassa watershed, with less than 400 mm of blue water per year. These areas witnessed a decreasing trend of blue water (figure 22). The annual precipitation has a decreasing pattern from eastern to western, which plays an important role in controlling the spatial distribution of blue water resources based on their similarity in spatial distribution.

The results reveal that the average blue-water potential of Hawassa watershed (mm yr^{-1}) is 638.5 mm. Blue-water potentials reach up to 1216 mm year^{-1} in some catchments such as Wondo-Genet, Wondo-Wosha, and Toga-Weransa, which are located on the eastern part of Lake Hawassa watershed. Besides, the western part and around the town represents poor potential due to higher potential evapotranspiration rate as well as urbanization in that catchment.

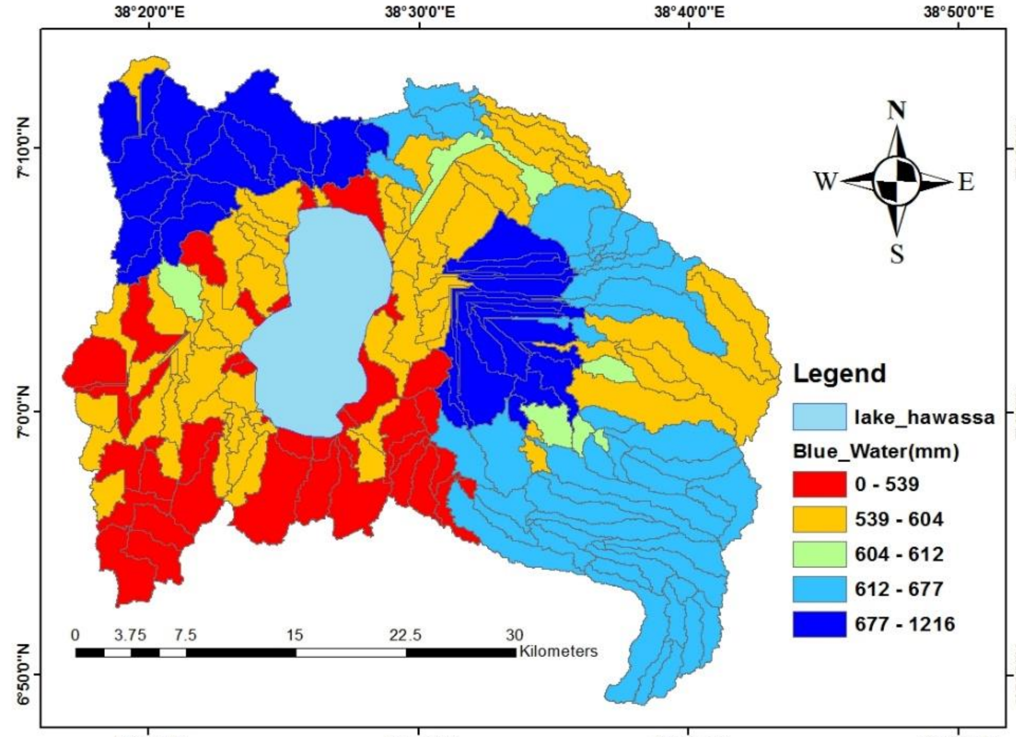

Figure 22. Spatial distribution of simulated average (1990–2015) annual blue-water.

To show the spatial distribution of precipitation, mean annual rainfall is depicted over the study Area (Cuceloglu et al., 2017). Then this is used to know which catchment receive the highest average annual rainfall where major water resource of Lake Hawassa Watershed is located figure (23)

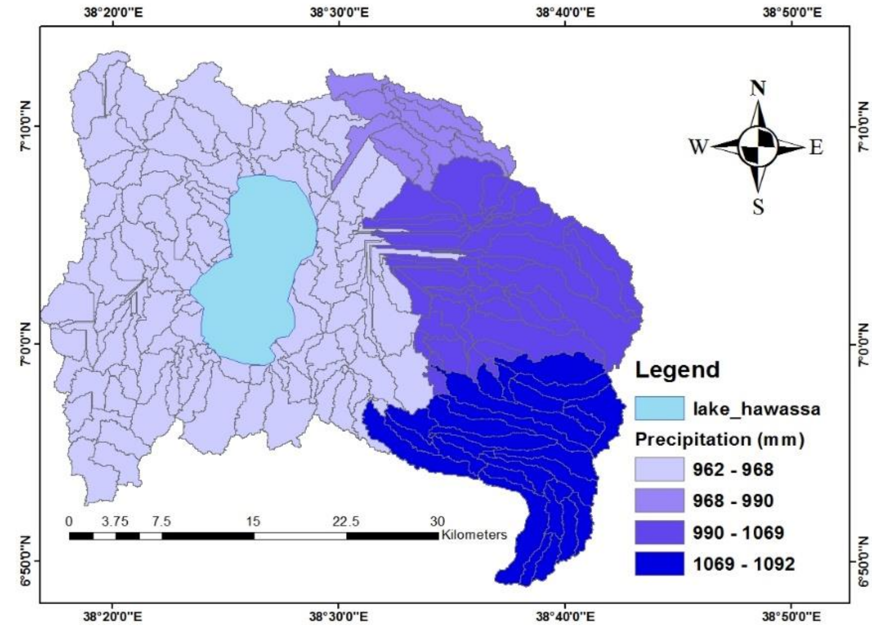

Figure 23. Spatial distribution of simulated average (1990–2015) annual precipitation.

According to the prediction of water potential, the highest magnitude of blue water and surface runoff are recorded in 1997/98 years (table 17).This indicate that this value was recorded due to El Niño-Southern Oscillation (ENSO) phenomena during that year in Ethiopia. We can see from the table 17, below that the average annual blue-water potential (water yield and deep aquifer recharge) of Lake Hawassa Watershed is 854 million m^3. Whereas the green-water flow (actual evapotranspiration) (ET) is 629 million m^3 and green water storage (soil moisture) is 82 million m^3.

Table 17. Yearly average water balance components (million-m3 yr^{-1}) of study area.

YEAR	Blue water (Mm3)	Precipitation (Mm3)	Green water storage (Mm3)	Green water flow (Mm3)	surface runoff (Mm3)
1992	858.60	1429.98	105.88	703.47	100.46
1993	838.22	1335.53	98.95	657.21	93.16
1994	871.25	1288.56	74.57	574.40	127.92
1995	831.46	1322.71	71.89	600.60	138.18
1996	1107.41	1607.14	98.89	687.24	169.22
1997	813.33	1400.95	104.52	693.40	105.65
1998	1126.39	1597.61	72.37	658.89	167.96
1999	650.80	1110.98	77.80	594.62	73.69
2000	712.92	1173.30	52.87	604.44	132.59
2001	937.09	1500.12	84.16	722.91	111.12
2002	738.23	1225.46	82.36	584.33	113.69
2003	758.48	1245.92	84.58	639.61	114.90
2004	671.97	1110.86	67.67	580.45	105.19
2005	939.20	1434.92	80.80	649.92	121.69
2006	1107.87	1658.09	92.80	695.33	171.62
2007	1170.30	1612.98	89.44	631.05	217.94
2008	778.26	1221.35	81.17	569.01	98.76
2009	515.82	970.95	74.31	562.79	54.88
2010	1041.51	1525.50	105.04	650.99	142.74
2011	942.93	1362.63	75.63	604.30	137.39
2012	606.74	994.18	70.92	528.75	71.44
2013	953.84	1447.29	71.61	641.67	150.36
2014	1006.47	1587.05	85.09	727.58	142.92
2015	522.77	941.18	69.01	552.76	57.53
Average	**854.24**	**1337.72**	**82.18**	**629.82**	**121.71**

The long-term trend of blue water is corresponding with increment in rainfall around the watershed (fig.24).

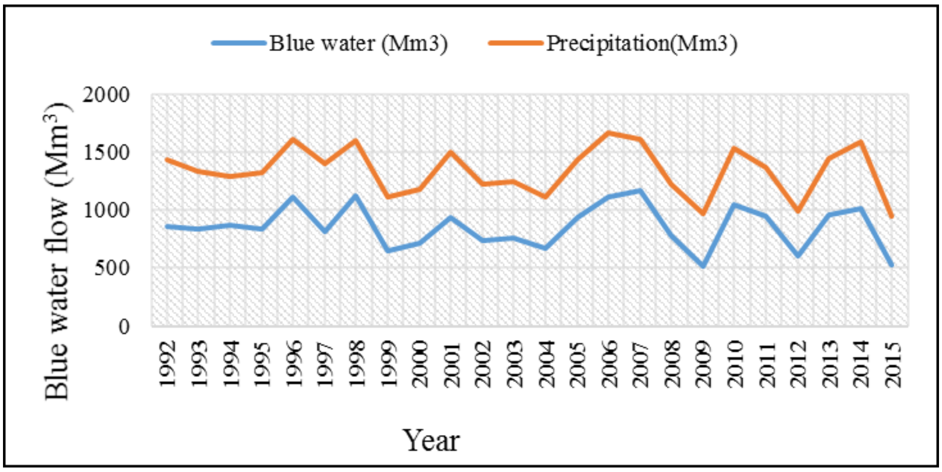

Figure 24. Long-term average annual values of blue water (million-m^3 yr^{-1}).

4.5.2. Green water flow availability

The spatial distribution of mean annual green water flow seems to have less variability in comparison to the spatial distribution of blue water in most of the areas in Lake Hawassa watershed (figure 25). The maximum green water flow was observed around Lake Hawassa with an average of more than 1675 mm yr^{-1}. The evaporation from the lake may be a possible reason for the higher amount of green water flow in the watershed.

The figure 25 below indicates a decreasing trend in green water flow for most of the areas in Hawassa watershed. For example, the green water flow for the areas located in upper watershed (around Wondo-Genet) indicates a decreasing trend. The spatial distribution of green water flow was found to be minimum in northern and eastern areas of the watershed. As shown in Figure 25, due to the amount of available water for transpiration and evaporation, green-water flows around Lake Hawassa (1600 mm year^{-1}) are higher in comparison to the North Eastern side (38 mm year^{-1}).

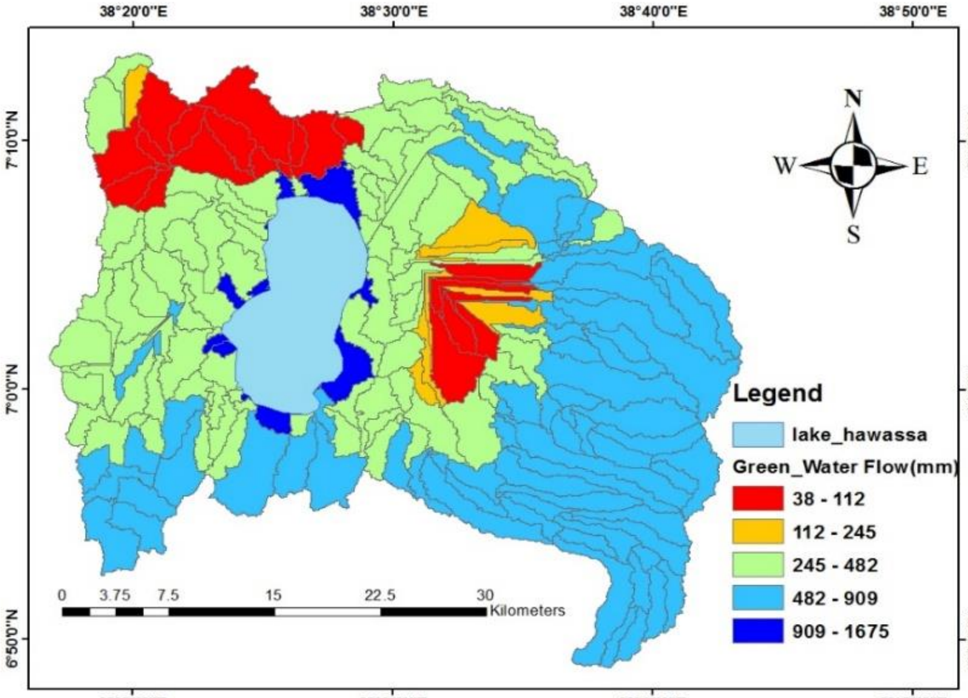

Figure 25. Spatial distribution of simulated average (1990–2015) of green water flow

As shown in figure 26 below, green water coefficient is the ratio of green water flow to the total green and blue water flows and it indicates the variation of green water flow around the watershed. High green water coefficient is around Lake Hawassa and low green water coefficient is around North West and Wondo-Genet area.

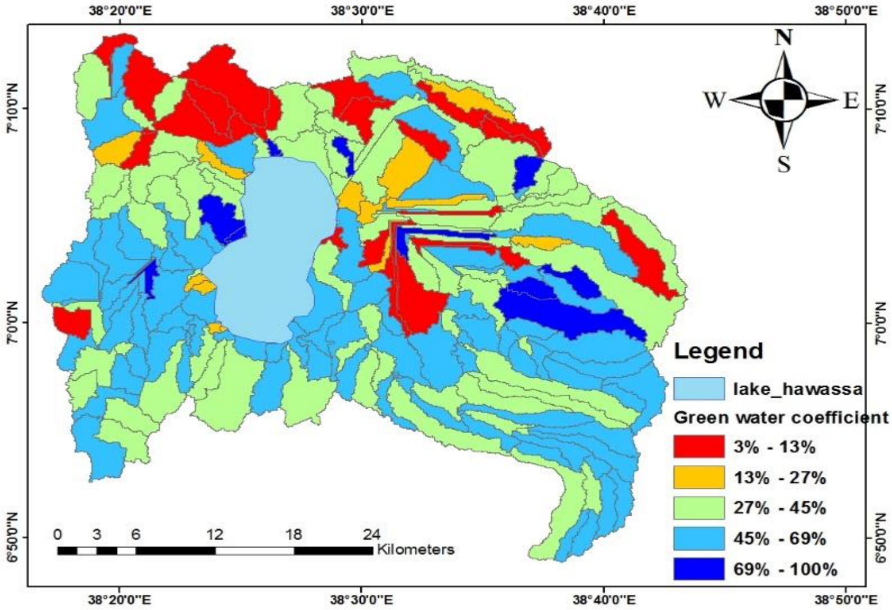

Figure 26. The green water coefficient from 1992 - 2015

4.5.3. Green water storage availability

The mean annual green water storage showed a variation from 50 mm to 224 mm throughout the watershed and its annual variability is comparatively small in comparison to blue and green water flow. The maximum green water storage was observed in the western area of the watershed. A decreasing trend in green water storage was noticed in most of the areas, for example, for the areas located in upper and lower watershed indicates a decreasing trend (figure 27).

In the current situation, small-scale rain fed agricultural activities play an important role for local villages. Therefore, optimal management strategies are necessary to achieve a balance between supplying water to Hawassa city and supporting the agricultural activities and economic growth as well as sustaining high water quality in this region.

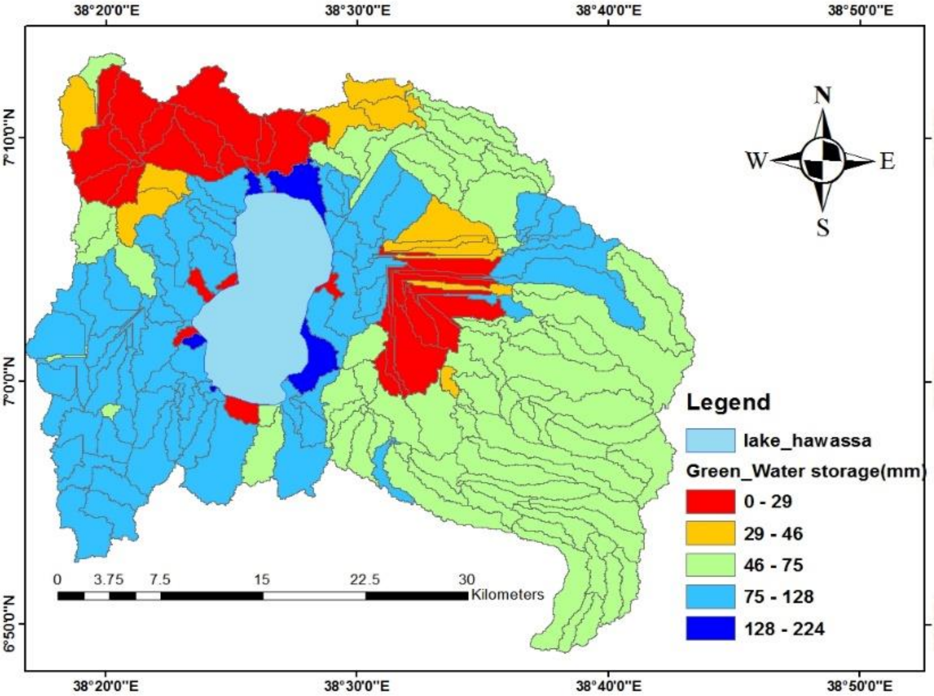

Figure 27. Spatial distribution of simulated average (1990–2015) green water storage.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

Socio-economic developments, rapid urbanization, and population increase have put pressures on water resources in the last few decades. Thus, matching the water demand of the Hawassa area requires effective water-management strategies and more projects to supply water from different areas. Quantification of available water is an essential part of the management of the water resource of Hawassa. This study contributes significant insights into the water availability of the city and its vicinity, at the watershed level.

Water resources availability, including internal renewable blue water, actual and potential ET as well as soil water, was estimated for Hawassa at the sub-basin spatial and monthly temporal resolutions.

The study was performed using the process-based semi-distributed hydrologic model SWAT, which integrates hydrological, agricultural and crop growth processes. Extensive calibration and validation, as well as sensitivity and uncertainty analyses were performed to increase the reliability of the model outputs. The model was calibrated against river discharge. SUFI-2 was used to calculate 95% prediction uncertainty for the outputs to characterize model uncertainty. Considering the conceptual model uncertainty (e.g. inter-basin water transfer, water use) as well as input data uncertainty and parameter uncertainty in such a large-scale hydrological model, presentation of the freshwater availability as a 95PPU band is useful for the water resources management and planning in the individual regions and for the country as a whole.

The sensitivity analysis using the SWAT model has pointed out ten most important parameters that control the stream flow of the studied watershed. On the other hand, model calibration and validation have shown that the SWAT model simulated the flow quite satisfactorily. Performance of the model for both the calibration and validation watershed was found to be reasonably good with Nash-Sutcliffe coefficients (NSE) values of 0.66 and coefficient of determination (R^2) values of 0.71 for the calibration and Nash-Sutcliffe coefficients (NSE) values of 0.59 and coefficient of determination (R^2) values of 0.61 for validation.

The results reveal that the annual blue-water potential (water yield and deep aquifer recharge) of Lake Hawassa Watershed is 854 million m^3, Whereas the green-water flow (actual evapotranspiration) (ET) is 806 million m^3 and green water storage (soil moisture) is 149 million m^3. Watersheds located around Wondo-Genet yield more blue-water resources compared to watersheds at the western side. The model highlights the water potential of the catchment under current circumstances and gives an insight into its spatiotemporal distribution over the watershed.

5.2. Recommendations

Water resources on the Wondo-Genet side encompass high water potential. These catchments are not affected by urbanization. Therefore, optimal management strategies in these catchments play a significant role in balancing water supply and local activities (agriculture, energy production, recreation etc.). In addition, protection of these catchments in terms of not only water quantity but also quality is vital to the area.

Watersheds supplying drinking water on the Eastern side are more reliable and more abundant. However, the majority of the population (thereby most of the water demand) is on the Western side around Hawassa city; freshwater resources are mostly located on the Eastern side and are outside the city boundaries. Therefore, water transfers from these catchments are vital to meeting the water demands of Hawassa.

More detailed analysis in the study area covering quantitative assessment of each watershed for different scenarios such as drought, socio-economic change, land-use conditions, as well as climate change scenarios, could provide more information and significant knowledge of value to policy-makers, local administrators and experts.

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APPENDICES

Appendix1: Long-term average (1992-2015) hydrological components at Subbasin level

SUBBASIN	PRECIP. (mm)	PET (mm)	ET (mm)	SW (mm)	Blue-water (mm)	Percolation (mm)	Surface runoff (mm)	GW_Q (mm)	WYLD (mm)	LAT_Q (mm)	DA_RCHG (mm)
1	970.86	1226.81	399.01	30.53	663.44	446.01	63.42	356.86	571.69	62.30	91.75
2	970.86	1225.17	398.94	30.61	663.92	452.63	63.57	362.16	571.75	55.60	92.17
3	970.86	1230.29	462.35	62.44	595.28	425.90	62.11	340.83	508.40	20.37	86.87
4	970.86	1226.00	398.13	30.79	664.59	449.34	63.53	359.53	572.57	59.74	92.02
5	970.86	1231.47	482.46	71.53	572.53	417.30	61.60	333.97	488.31	9.36	84.21
6	962.24	1232.22	282.08	34.23	749.65	342.68	179.39	274.11	679.87	157.92	69.78
7	962.24	1232.85	432.68	58.71	599.41	294.04	113.12	235.23	529.33	122.25	70.09
8	962.24	1227.19	124.23	8.54	924.31	524.38	250.78	419.43	837.61	62.67	86.70
9	962.24	1229.19	118.87	7.66	915.16	439.94	253.34	351.89	843.01	149.91	72.15
10	970.86	1230.32	483.93	72.80	571.18	416.03	62.78	332.95	486.85	7.99	84.33
11	962.24	1225.55	92.48	3.71	932.15	404.23	263.58	323.33	869.42	201.77	62.73
12	962.24	1223.80	419.45	39.59	615.29	391.80	82.69	313.53	542.68	68.17	72.61
13	962.24	1229.98	72.94	0.11	972.82	417.73	272.58	334.12	888.93	198.81	83.89
14	962.24	1222.83	72.61	0.14	973.83	454.84	272.68	363.81	889.26	161.92	84.58
15	962.24	1230.85	72.89	0.12	972.75	396.23	272.85	316.92	888.99	220.09	83.77
16	970.86	1236.43	471.14	62.27	585.98	435.04	54.00	348.15	499.63	10.55	86.35
17	962.24	1229.34	72.90	0.11	972.68	398.99	272.89	319.13	888.98	217.28	83.70
18	962.24	1225.89	72.76	0.13	972.78	431.87	275.01	345.42	889.10	182.42	83.68
19	970.86	1238.19	471.68	62.20	585.42	435.06	53.95	348.17	499.10	10.04	86.32
20	962.24	1230.46	72.88	0.12	972.83	403.45	273.34	322.70	888.99	212.38	83.84
21	970.86	1230.92	483.08	71.75	572.02	419.98	61.97	336.11	487.70	5.70	84.32
22	970.86	1231.46	479.75	73.25	569.46	385.48	63.22	308.50	491.02	42.27	78.44
23	962.24	1224.83	72.61	0.14	973.72	449.07	272.68	359.20	889.26	167.70	84.46
24	962.24	1227.95	72.61	0.14	973.33	447.01	272.66	357.55	889.26	169.78	84.07
25	962.24	1226.53	71.31	0.21	987.91	454.61	291.61	363.61	890.54	144.54	97.37
26	962.24	1221.32	69.05	0.34	1003.79	550.33	317.96	440.16	892.75	24.72	111.04
27	962.24	1223.61	82.53	2.76	953.85	455.90	285.48	364.64	879.32	138.15	74.53
28	962.24	1227.23	72.88	0.12	972.63	409.21	273.22	327.30	889.00	206.76	83.64
29	962.24	1227.66	88.58	3.68	936.04	406.33	264.69	325.00	873.30	202.46	62.74
30	962.24	1222.80	413.23	71.04	619.94	320.38	111.54	256.35	548.85	116.96	71.09
31	962.24	1222.88	429.38	72.91	598.07	308.49	92.47	246.84	532.70	131.76	65.38
32	962.24	1231.24	72.93	0.11	972.76	406.22	272.75	324.91	888.95	210.17	83.81
33	962.24	1224.55	281.15	43.32	762.60	367.15	174.67	293.72	680.85	139.12	81.75
34	962.24	1221.17	441.20	82.35	567.62	248.32	89.11	198.69	520.87	183.46	46.75
35	970.86	1227.92	437.24	59.35	604.93	387.75	64.30	310.29	533.50	81.43	71.43
36	962.24	1221.41	452.45	79.14	550.20	194.20	84.67	155.40	509.67	230.79	40.53
37	962.24	1222.09	482.86	77.20	539.65	282.60	82.43	226.16	479.31	114.25	60.34

Appendix1. Continued

SUBBASIN	PRECIP. (mm)	PET (mm)	ET (mm)	SW (mm)	Blue-water (mm)	Percolation (mm)	Surface runoff (mm)	GW_Q (mm)	WYLD (mm)	LAT_Q (mm)	DA_RCHG (mm)
38	962.24	1227.56	248.47	32.96	789.79	360.64	191.28	288.52	713.55	161.71	76.24
39	962.24	1221.95	449.23	76.69	550.31	162.74	83.10	130.22	512.86	267.03	37.45
40	962.24	1221.54	450.12	84.59	576.23	300.25	91.52	240.24	511.95	120.21	64.29
41	962.24	1996.74	1255.99	224.06	537.25	149.45	88.71	119.57	527.30	289.17	9.95
42	962.24	1220.64	435.15	82.40	556.96	150.44	88.68	120.36	526.90	287.81	30.05
43	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
44	962.24	1221.53	427.39	78.85	555.65	126.63	85.53	101.32	534.68	322.53	20.97
45	962.24	1235.67	343.91	52.87	693.60	403.41	151.80	322.78	618.16	62.98	75.45
46	1069.71	1230.88	503.68	68.85	624.21	346.93	75.06	277.83	566.32	144.06	57.89
47	1069.71	1230.15	485.16	82.85	662.82	383.22	87.78	306.89	584.85	113.55	77.97
48	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49	962.24	1923.09	1196.98	200.84	519.48	278.13	82.28	222.59	479.49	119.04	39.99
50	1069.71	1232.95	485.12	85.99	667.68	353.17	90.44	282.83	584.86	140.98	82.82
51	962.24	1235.23	343.52	55.63	698.39	416.06	151.06	332.89	618.53	51.46	79.86
52	962.24	1220.56	450.16	79.47	559.60	217.92	85.70	174.38	511.95	208.32	47.65
53	1069.71	1235.85	466.27	88.03	650.66	235.42	92.24	188.51	603.59	275.77	47.06
54	962.24	1221.28	449.61	83.42	584.80	326.27	91.72	261.06	512.46	94.49	72.35
55	1069.71	1221.67	235.24	35.59	944.02	663.07	42.51	530.85	834.68	128.78	109.34
56	1069.71	1221.02	530.29	81.37	629.28	445.09	85.49	356.48	539.83	8.86	89.44
57	1069.71	1221.01	530.25	81.39	629.37	445.84	85.50	357.08	539.88	8.14	89.49
58	962.24	1220.89	450.66	85.03	576.86	317.03	92.02	253.66	511.41	102.39	65.46
59	962.24	1221.30	438.28	77.68	563.93	153.62	83.94	122.93	523.82	286.25	40.11
60	1069.71	1222.02	492.98	73.48	632.70	167.43	77.46	134.11	576.92	331.88	55.78
61	962.24	1220.18	450.53	85.06	577.10	317.07	92.05	253.70	511.53	102.44	65.57
62	1069.71	1219.32	207.65	33.24	994.27	705.47	39.51	564.79	862.27	116.95	132.00
63	1069.71	1219.44	252.75	41.78	949.13	649.49	47.71	519.99	817.18	119.64	131.95
64	1069.71	1233.62	491.70	86.01	645.53	350.89	90.19	281.01	578.29	136.93	67.24
65	962.24	1220.38	449.97	84.87	577.00	308.00	91.87	246.44	512.10	112.26	64.91
66	962.24	1219.71	177.81	29.12	917.51	647.26	39.27	517.78	784.06	97.74	133.45
67	962.24	1568.83	813.07	119.07	531.82	266.95	90.90	213.59	514.04	156.22	17.78
68	962.24	1220.02	450.00	85.15	576.56	306.97	92.17	245.61	512.06	112.95	64.50
69	962.24	1219.60	450.09	85.65	574.91	314.49	92.74	251.63	511.97	104.78	62.93
70	1069.71	1219.45	250.02	37.28	950.68	656.12	43.38	525.31	819.93	120.08	130.75
71	1069.71	1219.31	40.97	0.06	1216.68	915.37	7.75	732.78	1028.92	105.42	187.76
72	962.24	1220.17	449.65	84.54	576.64	295.62	91.48	236.54	512.42	125.34	64.23
73	962.24	1220.10	436.74	81.11	557.92	207.19	87.83	165.78	525.33	230.33	32.59
74	962.24	1219.67	150.18	18.89	898.46	521.30	105.20	417.00	811.70	185.38	86.75
75	962.24	1219.56	39.08	0.04	1038.47	567.15	118.83	453.67	922.77	237.00	115.70
76	1069.71	1219.26	40.97	0.06	1216.88	921.14	7.75	737.40	1028.92	99.65	187.96

Appendix1. Continued

SUBBASIN	PRECIP. (mm)	PET (mm)	ET (mm)	SW (mm)	Blue-water (mm)	Percolation (mm)	Surface runoff (mm)	GW_Q (mm)	WYLD (mm)	LAT_Q (mm)	DA_RCHG (mm)
77	1069.71	1126.02	494.69	80.45	643.72	300.68	88.69	240.78	575.00	185.41	68.71
78	962.24	1220.22	426.94	78.84	555.90	125.18	85.53	100.16	535.13	324.43	20.77
79	962.24	1219.65	38.77	0.06	1090.46	817.32	11.78	653.80	923.01	94.18	167.45
80	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
81	962.24	1219.62	38.54	0.06	1009.34	512.52	11.67	409.98	923.34	399.32	86.00
82	962.24	1223.96	466.47	77.09	535.13	224.49	82.20	179.66	495.68	188.96	39.45
83	962.24	1221.79	463.42	80.92	556.50	272.50	87.09	218.06	498.69	139.10	57.81
84	1069.71	1229.15	488.86	71.49	626.50	129.38	75.45	103.63	581.02	376.06	45.48
85	1069.71	1219.47	222.37	30.87	977.21	693.17	37.23	554.96	847.58	116.82	129.63
86	962.24	1220.65	452.41	77.90	550.15	196.02	83.89	156.86	509.71	229.80	40.44
87	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
88	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
89	1069.71	1219.33	40.97	0.06	1216.65	914.56	7.75	732.14	1028.92	106.23	187.73
90	962.24	1219.68	38.77	0.06	1090.98	826.00	11.78	660.74	923.01	85.51	167.98
91	1069.71	1220.26	515.93	80.60	625.50	325.09	84.81	260.39	554.12	143.91	71.37
92	962.24	1220.12	38.77	0.06	1090.28	814.90	11.77	651.86	923.01	96.61	167.27
93	962.24	1225.18	407.86	66.23	608.72	241.47	109.68	193.22	554.25	203.11	54.47
94	1069.71	1134.38	500.61	78.00	619.23	281.58	86.76	225.49	569.07	200.51	50.16
95	1069.71	1150.24	538.15	73.37	602.80	363.06	85.31	290.74	531.51	82.87	71.29
96	962.24	1220.83	433.97	80.59	558.19	150.66	87.45	120.54	528.10	290.01	30.10
97	962.24	1220.69	483.47	77.48	539.54	292.39	82.72	233.99	478.70	103.57	60.83
98	962.24	1220.55	484.20	77.38	538.75	290.97	82.41	232.87	477.98	104.56	60.77
99	962.24	1225.46	468.18	77.86	548.19	249.68	83.81	199.82	493.96	160.45	54.23
100	962.24	1220.39	485.82	77.94	537.41	314.46	82.95	251.65	476.33	78.90	61.08
101	1069.71	1150.63	539.45	73.40	601.47	365.44	85.10	292.66	530.17	79.34	71.30
102	1069.71	1219.47	159.48	19.63	1048.74	711.60	26.32	569.68	910.41	172.17	138.33
103	962.24	1226.96	474.38	78.39	538.55	276.13	84.83	220.97	487.76	126.78	50.79
104	962.24	1220.54	482.64	77.32	539.92	284.37	82.57	227.58	479.53	112.55	60.39
105	962.24	1220.60	471.32	78.37	547.11	260.02	84.04	208.09	490.82	146.74	56.29
106	962.24	1220.61	482.51	77.28	539.96	282.91	82.54	226.41	479.67	114.19	60.30
107	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
108	962.24	1219.70	482.19	77.30	540.39	281.84	82.57	225.56	479.99	115.54	60.41
109	962.24	1220.84	449.64	84.45	576.55	292.90	91.38	234.36	512.43	128.17	64.12
110	1069.71	1221.65	499.81	75.62	603.08	165.02	79.44	132.18	570.08	325.46	33.00
111	962.24	1220.33	483.47	77.51	539.46	293.35	82.75	234.76	478.70	102.58	60.75
112	962.24	1222.27	483.28	77.28	539.33	286.78	82.50	229.51	478.90	109.58	60.43
113	1069.71	1140.17	523.56	71.95	590.74	273.61	81.52	219.11	546.11	190.77	44.63
114	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
115	1069.71	1219.74	329.19	48.15	874.31	482.04	53.48	385.94	740.74	204.95	133.58

Appendix1. Continued

SUBBASIN	PRECIP. (mm)	PET (mm)	ET (mm)	SW (mm)	Blue-water (mm)	Percolation (mm)	Surface runoff (mm)	GW_Q (mm)	WYLD (mm)	LAT_Q (mm)	DA_RCHG (mm)
116	1069.71	1121.87	491.08	69.17	609.31	133.57	77.88	106.95	578.46	366.93	30.85
117	962.24	1913.35	1187.60	197.22	519.85	288.41	82.71	230.81	479.39	108.24	40.46
118	962.24	1219.99	210.44	22.98	847.51	454.24	97.90	363.37	751.49	199.50	96.02
119	1069.71	1219.55	40.92	0.06	1173.73	724.68	7.71	580.13	1028.89	296.20	144.84
120	1069.71	1220.01	360.94	52.86	844.84	389.93	57.87	312.20	708.95	260.92	135.90
121	962.24	1219.99	482.51	77.34	540.24	284.36	82.61	227.57	479.66	112.65	60.58
122	962.24	1221.67	471.76	68.40	514.87	119.62	189.38	95.70	490.31	181.33	24.55
123	1069.71	1141.52	525.29	71.80	597.41	277.77	81.94	222.45	544.31	184.38	53.11
124	962.24	1786.16	1042.17	146.65	521.54	104.30	73.16	83.48	509.08	331.59	12.47
125	962.24	1226.47	462.87	77.28	538.80	214.09	82.39	171.34	499.27	202.76	39.53
126	962.24	1230.59	466.77	80.77	552.34	296.49	88.56	237.25	495.34	110.29	57.00
127	962.24	1224.78	460.44	75.11	535.40	194.39	79.77	155.57	501.71	227.52	33.68
128	962.24	1221.97	482.81	77.21	539.71	282.78	82.45	226.31	479.36	114.10	60.35
129	962.24	1220.99	482.24	77.19	540.04	279.29	82.45	223.51	479.93	118.16	60.11
130	962.24	1225.07	482.75	76.91	539.25	275.37	82.11	220.37	479.43	121.92	59.82
131	962.24	1226.70	453.74	77.97	548.12	189.80	83.23	151.89	508.38	235.33	39.73
132	962.24	1220.19	38.75	0.07	1090.35	815.15	11.62	652.06	923.02	96.53	167.33
133	962.24	1220.03	117.18	16.00	912.15	448.56	26.65	358.82	844.73	369.67	67.41
134	1067.68	1143.06	529.50	72.29	591.95	308.20	83.04	246.81	539.09	147.61	52.86
135	1069.71	1220.57	432.38	63.91	742.38	238.57	68.32	191.04	637.49	330.44	104.88
136	1069.71	1126.17	500.04	69.83	614.25	176.04	78.79	140.97	569.52	314.56	44.74
137	962.24	1223.35	482.34	76.99	539.61	275.33	82.22	220.34	479.83	122.26	59.78
138	1069.71	1139.59	521.20	71.71	602.68	280.30	81.70	224.47	548.42	186.21	54.26
139	962.24	2394.16	1675.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
140	962.24	1221.13	482.09	77.15	540.10	277.57	82.41	222.14	480.09	120.07	60.02
141	962.24	1220.97	482.27	77.20	540.10	279.71	82.47	223.85	479.90	117.69	60.20
142	962.24	1219.94	481.92	77.23	540.22	278.85	82.51	223.16	480.25	118.87	59.96
143	1069.71	1219.79	272.73	37.87	860.19	418.99	43.65	335.44	797.12	334.27	63.07
144	1069.71	1223.71	486.68	72.04	605.15	116.37	75.93	93.21	583.18	390.76	21.97
145	962.24	1220.60	482.44	77.27	539.85	282.51	82.52	226.09	479.73	114.67	60.12
146	962.24	1473.22	738.90	89.98	499.95	279.77	82.47	223.90	479.88	117.61	20.07
147	962.24	1223.88	482.48	76.97	539.54	275.50	82.19	220.48	479.69	121.97	59.85
148	962.24	1223.65	467.74	73.00	524.26	191.95	77.40	153.62	494.43	225.05	29.83
149	962.24	1220.88	453.54	69.65	527.42	106.00	73.33	84.84	508.62	329.26	18.81
150	1069.71	1124.40	491.89	68.71	609.60	134.84	77.34	107.97	577.64	365.37	31.96
151	962.24	1220.01	482.16	77.28	540.25	281.19	82.55	225.04	480.02	116.24	60.23
152	962.24	1221.25	481.67	77.05	540.17	273.50	82.30	218.88	480.50	124.66	59.67
153	962.24	1223.11	482.63	77.07	539.59	278.61	82.31	222.97	479.54	118.59	60.05
154	1069.71	1125.85	496.13	69.31	605.18	152.11	78.06	121.80	573.41	343.13	31.77

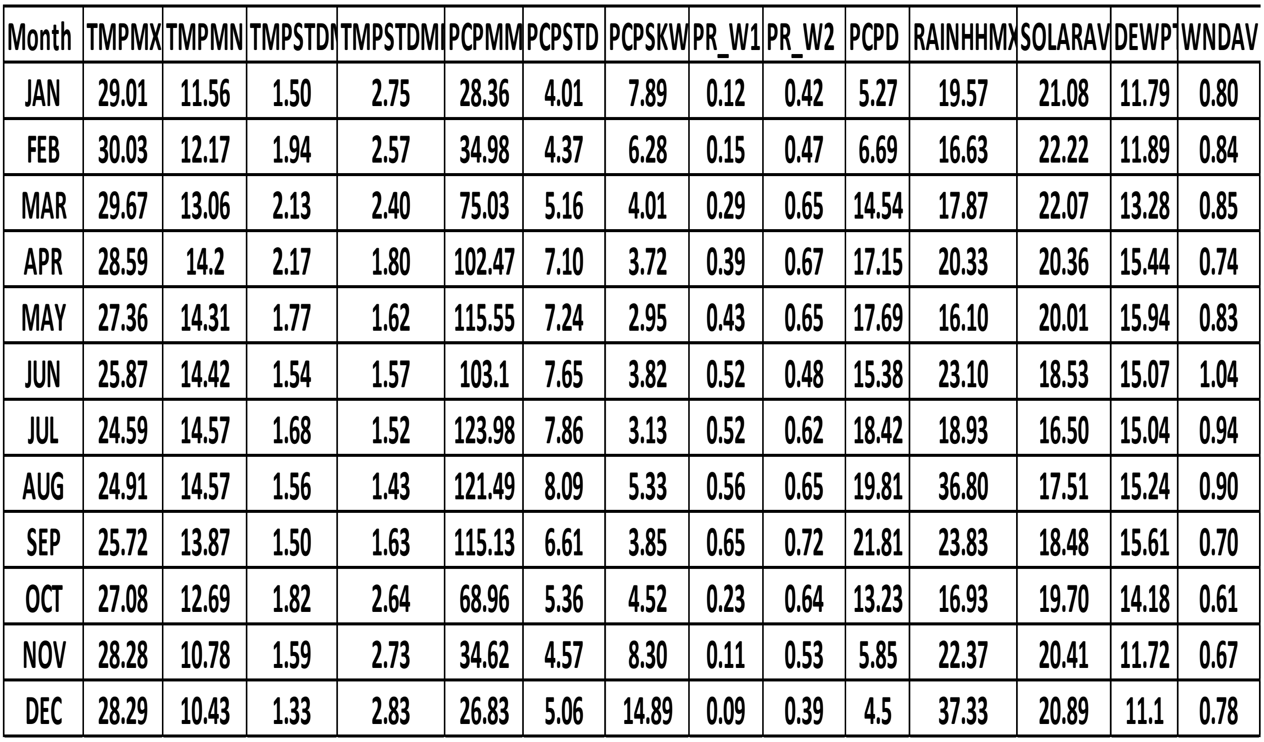
Appendix1. Continued

SUBBASIN	PRECIP. (mm)	PET (mm)	ET (mm)	SW (mm)	Blue-water (mm)	Percolation (mm)	Surface runoff (mm)	GW_Q (mm)	WYLD (mm)	LAT_Q (mm)	DA_RCHG (mm)
155	1069.71	1220.49	492.05	73.68	600.55	138.48	77.58	110.92	577.82	361.62	22.72
156	962.24	1222.19	482.46	77.12	539.79	278.88	82.37	223.19	479.72	118.44	60.07
157	962.24	1224.30	482.22	76.88	539.62	272.21	82.10	217.85	479.95	125.61	59.67
158	962.24	1223.57	482.97	76.84	538.92	274.18	81.99	219.43	479.20	122.99	59.72
159	962.24	1222.36	454.08	69.65	526.76	106.47	73.32	85.22	508.08	328.26	18.68
160	962.24	1222.23	464.47	72.33	525.20	137.71	76.79	110.21	497.68	283.17	27.52
161	962.24	1229.82	456.47	85.60	577.34	337.06	92.61	269.69	505.58	75.94	71.76
162	962.24	1225.98	471.94	77.65	540.73	247.52	82.93	198.09	490.21	159.73	50.52
163	962.24	1220.66	455.52	70.13	525.54	111.91	73.91	89.57	506.64	320.79	18.91
164	1092.30	1152.49	531.08	71.82	635.04	371.50	76.56	297.11	560.82	112.96	74.22
165	962.24	1227.32	466.83	79.60	543.21	262.42	85.47	209.99	495.28	147.39	47.93
166	962.24	1224.21	479.90	74.37	532.43	232.39	78.97	185.99	482.27	170.88	50.16
167	1092.30	1140.15	517.05	70.30	622.26	290.79	73.12	232.55	574.90	211.17	47.36
168	962.24	1226.64	480.86	74.07	532.89	252.19	78.95	201.83	481.32	150.15	51.57
169	962.24	1224.05	464.59	72.19	524.85	136.50	76.61	109.25	497.57	284.44	27.28
170	1092.30	1139.47	522.81	71.07	641.80	317.49	74.35	253.91	569.13	177.47	72.67
171	962.24	1227.50	480.40	78.82	545.69	304.42	84.32	243.61	481.75	92.99	63.94
172	962.24	1223.74	371.10	55.61	671.66	294.34	61.17	235.50	590.97	235.50	80.69
173	962.24	1227.80	473.49	76.31	534.88	246.75	81.21	197.47	488.67	160.68	46.21
174	1069.71	1223.33	488.26	72.36	603.81	121.94	76.30	97.67	581.61	383.26	22.20
175	962.24	1227.75	489.06	75.59	528.48	290.75	81.19	232.69	473.12	101.14	55.36
176	962.24	1222.89	404.47	62.13	643.07	304.49	67.66	243.64	557.63	185.50	85.44
177	962.24	1227.93	494.69	77.01	529.39	341.58	81.83	273.37	467.50	44.05	61.89
178	1092.30	1154.15	530.33	71.21	629.62	352.36	76.39	281.80	561.60	133.04	68.03
179	962.24	1224.34	490.94	75.85	530.43	298.48	80.69	238.88	471.24	92.03	59.19
180	962.24	1228.55	485.03	79.95	545.33	357.76	85.44	286.29	477.11	33.89	68.22
181	1092.30	1149.54	525.54	70.73	632.41	310.43	75.23	248.25	566.38	180.91	66.02
182	1092.30	1157.19	531.31	71.16	634.37	359.43	76.45	287.46	560.58	124.89	73.79
183	962.24	1226.48	487.26	75.58	534.01	292.43	80.17	234.04	474.92	102.28	59.08
184	962.24	1232.47	496.14	76.17	527.58	322.15	82.53	257.82	466.05	61.34	61.53
185	962.24	1229.95	488.31	74.63	530.50	257.19	79.35	205.83	473.86	137.28	56.64
186	962.24	1229.37	493.21	76.38	529.44	315.38	81.17	252.40	468.97	72.38	60.47
187	1088.47	1152.87	528.21	70.71	634.65	337.09	75.99	269.58	561.83	148.94	72.82
188	962.24	1227.72	493.12	76.41	528.13	331.56	81.04	265.35	469.07	56.43	59.05
189	1092.30	1147.17	528.11	71.77	637.91	356.26	76.15	284.93	563.79	131.58	74.11
190	1092.30	1144.21	527.84	72.22	638.92	361.76	76.57	289.32	564.08	125.95	74.84
191	1092.30	1150.19	530.35	71.72	636.68	369.39	76.57	295.43	561.56	115.80	75.12
192	1092.30	1137.01	527.86	73.29	641.57	387.93	78.41	310.26	564.01	97.88	77.56

Appendix1. Continued

SUBBASIN	PRECIP. (mm)	PET (mm)	ET (mm)	SW (mm)	Blue-water (mm)	Percolation (mm)	Surface runoff (mm)	GW_Q (mm)	WYLD (mm)	LAT_Q (mm)	DA_RCHG (mm)
193	962.24	1227.81	494.55	77.15	535.05	344.04	81.97	275.34	467.64	41.58	67.42
194	1092.30	1135.87	526.96	72.85	642.68	381.92	76.30	305.45	564.95	106.93	77.73
195	1092.30	1139.00	525.82	72.12	642.36	353.99	77.54	283.10	566.10	134.78	76.26
196	962.24	1228.12	499.23	77.26	537.20	371.49	81.92	297.31	462.97	9.51	74.23
197	962.24	1227.64	496.44	76.76	532.91	341.90	81.49	273.62	465.74	42.32	67.16
198	1092.30	1150.79	530.95	71.78	637.12	376.59	77.51	301.18	560.96	107.07	76.16
199	962.24	1229.79	499.68	77.20	537.36	372.78	81.87	298.34	462.51	7.82	74.85
200	1092.30	1145.82	528.54	71.93	638.60	360.19	77.45	288.07	563.37	125.92	75.23
201	1092.30	1149.90	530.71	71.88	637.21	361.97	76.88	289.49	561.19	122.54	76.02
202	1092.30	1136.94	525.77	72.74	641.91	369.42	78.32	295.45	566.13	118.59	75.77
203	1088.22	1152.32	529.83	71.20	634.69	360.29	76.69	288.15	560.10	123.32	74.59
204	962.24	1230.09	496.69	76.45	527.61	334.56	81.13	267.75	465.49	49.76	62.11
205	1092.30	1145.95	529.57	72.04	638.69	374.43	77.75	299.46	562.31	110.33	76.39
206	1092.30	1154.18	532.81	71.90	635.72	379.59	77.00	303.59	559.07	102.68	76.65
207	962.24	1228.53	496.81	76.64	528.17	342.59	81.36	274.18	465.38	41.39	62.78
208	1092.30	1157.14	531.81	70.97	634.63	358.59	76.45	286.79	560.09	125.24	74.54
209	1092.30	1154.57	531.12	71.31	635.39	359.62	76.83	287.61	560.79	124.55	74.59
210	1092.30	1157.88	532.09	71.02	634.14	356.19	76.52	284.86	559.84	127.34	74.29
211	1091.26	1158.51	532.96	71.09	634.08	370.50	76.81	296.31	558.46	111.36	75.61
212	1089.13	1156.52	531.78	71.27	633.77	366.98	76.65	293.50	558.60	115.17	75.17
213	1092.30	1158.60	533.30	71.02	634.00	367.02	76.52	293.53	558.61	115.27	75.40
214	1073.96	1143.16	525.11	70.85	632.74	361.62	74.09	289.21	557.83	122.32	74.91
215	1089.41	1158.33	532.70	71.06	633.80	375.37	74.88	300.20	557.81	107.77	75.99
216	1090.30	1157.62	532.30	71.07	633.90	365.76	75.47	292.52	558.64	117.61	75.26
Average	**999.87**	**1268.04**	**470.76**	**61.43**	**638.50**	**332.79**	**90.97**	**266.30**	**571.48**	**147.71**	**67.02**

Appendix 2: Weather generator (WGEN) parameters used by the SWAT for Lake Hawassa watershed



Month	TMPMX	TMPMN	TMPSTDM	TMPSTDMN	PCPMM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD	RAINHHMX	SOLARAV	DEWPT	WNDAV
JAN	29.01	11.56	1.50	2.75	28.36	4.01	7.89	0.12	0.42	5.27	19.57	21.08	11.79	0.80
FEB	30.03	12.17	1.94	2.57	34.98	4.37	6.28	0.15	0.47	6.69	16.63	22.22	11.89	0.84
MAR	29.67	13.06	2.13	2.40	75.03	5.16	4.01	0.29	0.65	14.54	17.87	22.07	13.28	0.85
APR	28.59	14.2	2.17	1.80	102.47	7.10	3.72	0.39	0.67	17.15	20.33	20.36	15.44	0.74
MAY	27.36	14.31	1.77	1.62	115.55	7.24	2.95	0.43	0.65	17.69	16.10	20.01	15.94	0.83
JUN	25.87	14.42	1.54	1.57	103.1	7.65	3.82	0.52	0.48	15.38	23.10	18.53	15.07	1.04
JUL	24.59	14.57	1.68	1.52	123.98	7.86	3.13	0.52	0.62	18.42	18.93	16.50	15.04	0.94
AUG	24.91	14.57	1.56	1.43	121.49	8.09	5.33	0.56	0.65	19.81	36.80	17.51	15.24	0.90
SEP	25.72	13.87	1.50	1.63	115.13	6.61	3.85	0.65	0.72	21.81	23.83	18.48	15.61	0.70
OCT	27.08	12.69	1.82	2.64	68.96	5.36	4.52	0.23	0.64	13.23	16.93	19.70	14.18	0.61
NOV	28.28	10.78	1.59	2.73	34.62	4.57	8.30	0.11	0.53	5.85	22.37	20.41	11.72	0.67
DEC	28.29	10.43	1.33	2.83	26.83	5.06	14.89	0.09	0.39	4.5	37.33	20.89	11.1	0.78

Appendix 3. Soils parameters and legend used in SWAT model

NLAYERS	Number of layers in the soil (min 1 max 10)
HYDGRP	Soil hydrologic group (A,B,C,D)
SOL_ZMX	Maximum root depth of the soil
ANION_EXCL	Fraction of porosity from which an ions are exchanged
SOL_CRK	Crack volume potential of soil
TEXTURE	Texture of the layer
SOIL_Z	Minimum depth from soil surface to bottom of layer
SOL_BD	Moist bulk density
SOL_AWC	Available water capacity of soil surface to bottom of the layer
SOL_K	Saturated hydraulic conductivity
SOL_CBN	Organic carbon content
CLAY	Clay content
SILT	Silt content
SAND	Sand content
ROCK	Rock fragmented content
SOL_ALB	Moist soil albedo
USLE_K	Soil erodibility factor(k)