QUANTIFICATION OF BLUE AND GREEN WATER RESOURCES IN LAKE HAWASSA CATCHMENT

MSc THESIS

ADDISU TAMENE DINAGA

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ADDISU TAMENE DINAGA

ADVISOR: SIRAK TEKLEAB (PhD)
CO-ADVISOR : SHEMELES ASSEFA (PhD)

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Teshale Tadesse (MSc)	____________________	________________
Name of the Chairperson	Signature	Date
Sirak Tekleab (PhD)	____________________	________________
Name of major advisor	Signature	Date
Shemeles Assefa (PhD)	____________________	________________
Name of co-advisor	Signature	Date
Alemayehu Muluneh (PhD)	____________________	________________
Name of Internal Examiner	Signature	Date
Adane Abebe (PhD)	____________________	________________
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____________________	____________________	________________
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STATEMENT OF THE AUTHOR

I declare that the work presented here is my own original work and all contributions have been acknowledged properly. In addition, this thesis has not been previously submitted and presented to any other for a degree or diploma award.

Name: Addisu Tamene Dinaga

Signature: ______________________

Date: __________________________

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LISTS OFABBREVIATIONS/ACRONYMS

ASCE	American Society of Civil Engineers
BCM	Billion cubic meter
CN	Curve number
CSA	Central Statistics Agency of Ethiopia
DEM	Digital Elevation Model
EFRs	Environmental Flow Requirements
ET_o	Reference evapotrainspiration
FAO	Food and Agriculture Organization of the United Nations
GIS	Global Information System
GTP	Growth and Transformation Plan of Ethiopia
GWP	General Water partnership
ITCZ	Inter-tropical convergence zone
IWRM	Integrated Water resources Management
Kc	Crop coefficient
km^2	Square kilometer
l/c/day	Liter per capital per day
m.a.s.l	Mater above sea level
Mm^3	Million meter cube
MoWR	Ministry of Water Resources
NMSA	National Meteorological services Agency
SNNPRS	South Nation Nationality of People Region state
SWAT	Soil and Water Assessment Tool
SWAT-WB	Soil and Water Assessment Tool Water Balance
TLU	Tropical livestock unit
UNW-DPAC	UN-Water Decade Programme on Advocacy and Communication
USDA SCS	United States Department of Agriculture Soil Conservation Service)
VW	Virtual water
WB	Water balance
WHO	World health organization
WF	Water footprint
VSA	Variable source area

ABSTRACT

In most cases knowing the potential, availability and use of fresh water in a catchment would help to increase the productivity of agriculture, to improve ways and means of water management system. This Study was conducted in Lake Hawassa catchment, located in the central rift valley lakes basin of Ethiopia, to quantify the blue and green water resource using SWAT-WB, lake water balance using excel spread sheet application and water consumption demand of different water use sectors. Model sensitivity analysis shows the soil evaporation compensation factor (Esco), the soil available water content (SOL_AWC) and depth from soil surface to bottom of layer (Sol_Z) as the most sensitive parameters. The performance of the model has been evaluated through calibration and validation process. The result of SWAT-WB calibration and validation for stream flow measured with coefficient of determination (R^2) and Nash-Sutcliffe model efficiency (ENS) were 0.69, 0.66, 0.67 and 0.65 respectively which indicated that a good agreement between observed and simulated values. The calibrated parameters were transferred to un-gauged part of the catchment to simulate hydrological components based on the hydrologic response unit (HRU) similarity. The long-term mean annual blue and green water flow and green water storage volume results obtained from model output found to be 500.24, 954.86 and 826.14 Mm^3 respectively. In addition simulation of the lake water balance shown that the net blue water storage avilable in the lake was 1017.51Mm^3. The spatial and seasonal values of the result indicate that there exists a significant difference in both spatial and seasonal distributions of blue and green water flows in the catchment. The water consumption result shows that there is agricultural water consumption dominancy over other water users, accounting for 70% of the total consumption and the remaining 30% was for the other sectors. The overall consumption of water in the catchment is about 6.11% of the total Blue and Green water potential of 3.3 billion m^3 per year which indicates the catchment water resource is underutilized. This study will help to prepare a future plan for the water resources development and management in the catchment, since plenty of water resource is available there. The water consumption level in the catchment is very small so further investigation is essential to use the available water resource potential of the catchment than ever so.

Key words: SWAT-WB model, Blue water, Green Water, water consumption, Lake Hawassa catchment.

1. INTRODUCTION

1.1. Background and Justification

In recent years, scientific community largely focuses on the quantification of water resources by developing different frameworks. The Blue water and Green water definition (Falkenmark, 1995; Falkenmark and Rockström, 2006); water accounting framework (Molden, 1997; Karimi, 2014); the water foot print framework (Hoekstra et al., 2011). All these frameworks were developed mainly due to the fact that water scarcity is a pressing issue at a global scale. Recently, owing to increasing in population, the needs of water for various consumptions in the one hand and the environmental changes due to (e.g. land use and climate) on the other hand pose an additional threat to the limited freshwater availability. Among the various needs, Agriculture consumed large amount of water (Rockström, 2003).

Water is at the foundation of sustainable development as it is the common denominator of all global challenges: energy, food, health, peace and security, and poverty eradication as pointed out by the United Nation (UN) (UN, 2012).

Uncertainties regarding future climate, trends in population growth, and changes in lifestyle are likely to promote significant increases in risks associated with environmental and human water security. Based on Dulce et al. (2014) study it has been reported that 80% of the world's population is exposed to high levels of water security risk, with consumptive water use being one of the strongest stressors. Currently, agriculture accounts for 70% of global freshwater withdrawals, and more than 90% of its consumptive use. It has been estimated that there will, by 2050, be a 70% increase in demand for food production globally, and up to a 100% increase in developing countries (Dulce et al., 2014).

It is generally recognized that fresh water is regarded as one of the most important natural resources for all socio-economic development and a basic input for environmental management. Failure to successfully develop and appropriately utilize this resource leads to a progressively declining economy and degraded environment (Mekiso, n.d.).

The freshwater cycle can be partitioned into two kinds "green" and "blue" water in accordance with the hydrological processes and storage type involved. The concepts of blue water and green water were firstly introduced by Falkenmark (1995), and developed by others. By definition, blue water is the sum of surface runoff and deep aquifer recharge. Green water flow is the actual evapotranspiration (AET) released to the atmosphere through a combination of evaporation from soil and water bodies, and transpiration from vegetation. Green water storage (soil moisture) is the amount of water in the soil profile at the end of a time-period (Falkenmark and Rockström, 2006; Rockström et al., 2010; Zongxue and Depeng, 2014).

Conventional approaches to water management have focused on managing solely the blue component of the water cycle. Different authors, however, recommend to including green water in water management studies. Rainfed agriculture is the largest (green) water user and irrigated agriculture is the largest blue water user in worldwide scale. There are now many studies that include the green component of the water cycle (Vanham and Bidoglio, 2013).

Both blue and green water flows are made productive for human purposes. Blue water is used for industrial and domestic purposes and for irrigation in agriculture. Green water sustains crop production, grazing lands, forestry and terrestrial ecosystems. These systems provide food, fiber, biofuels, timber and livestock products and other ecosystem services that benefit human's livelihood (Schyns et al., 2015).

Joint management of blue and green water is useful for identifying critical hydrological situations where water abstractions, environmental flow and crop water requirements need to be met with reduced water resources, and for design of management practices needed to maintain required levels of blue water flow to downstream users so as to decrease blue water dependency (Calder, 2007).

Ethiopia is a developing country which is endowed with a number of lakes and large rivers which gives immense value to overall economic development. For instance, the country has 12 river basins, 11 fresh lakes, 9 saline lakes, 4 crater lakes and over 12 major swamps or wetlands (Milda, 2009).

Lake Hawassa Catchment is located in the Central Rift Valley lakes basin. Different water users (i.e., rural, urban, irrigated agriculture and industry) are present in the catchment. The catchment water resources (surface and groundwater) are extensively used for various purposes. However, the water resources for the various competing needs are not quantified yet in the catchment.

Thus, this research focused on the quantification of green and blue water resource at a catchment scale and to show water consumption share of water use sectors in the catchment and provide a baseline assessment which expected to assist in the planning and managements of the available resources. Such an assessment is a key to better understanding the entire picture of water consumption at the catchment level, and identifying ways to improve water management.

1.2. Statement of the problem

Freshwater is becoming increasingly scarce in many regions of the world, as result of both unsustainable land management and changes in rainfall patterns, as a consequence of global and regional climate change (Johansson et al., 2016). Moreover, the demand for water is increasing because of population growth, higher food demand, increased industrialization and urbanization. As demand for water, food, and energy increases, there is an increased competition for water resources between agriculture, livestock, fisheries, forestry, and other sectors, with unpredictable impacts for livelihoods and the environment (Johansson et al., 2016; FAO, 2017).

Population growth, urbanization, agricultural expansion, catchment land use change and excessive water abstraction are putting increasing pressure on the Lake Hawassa catchment fresh water resources and water management systems. However, the total amount of available surface fresh water resources in the catchment is not yet known.

Several studies in the area of water resources have been conducted in Lake Hawassa catchment, (e.g. Dessie, 1995; Gebreegziabher, 2004; Ayenew et al., 2007; AG Consult, 2007; Atnafu, 2014) among others. However these previous studies not quantified the whole of the water resource in the catchment in the form of different computing needs based on updated information and suitable methods.

It is necessary to find new approaches and tools for comprehensive assessment and management of water resources in the catchment. Currently the new approaches, green and blue water (Falkenmark et al., 1995), water accounting (Bastiaanssen, 1998) and water footprint (Hoekstra et al., 2011) have been emerging in scientific communities to promote efficient, equitable and sustainable water uses, and these studies believe that water resource should be quantified based on the concept of these paradigms to break new ground for water resources planning and management. This new approach (i.e.

quantification of blue and green water) was implemented in Lake Hawassa catchment for the purpose of estimating quantities of water resource in the catchment instead of using conventional water resource planning methods.

The assessment of total fresh water resource (Blue water and Green water) at catchment scale and total water consumption demand of multiple water use sectors helps to develop efficient, equitable, and sustainable water use and allocation system. Therefore, the result of this study contributes to a better understanding of the use of blue and green water resources and consequently to provide useful information for the planning and management of water resource in the catchment in the region as well.

1.3. Objectives of the study

1.3.1. General Objective

The main objective of this research is to quantify the blue and green water resource in Lake Hawassa catchment.

1.3.2. Specific Objectives

The specific objectives are:

- ✓ To estimate the water balance components of Tikur Wuha sub-catchment.
- ✓ To quantify the various water balance components of the Lake Hawassa.
- ✓ To estimate the annual and seasonal water availability in a form of the blue and green water flows and green water storage
- ✓ To quantify the water consumption of different water use sectors within the catchment.

1.4. Research questions

To achieve the research objective, these questions will be answered based on the data collection and analysis out puts.

- ✓ What is the total water resource potential (blue and green water) available in the catchment?
- ✓ What are the dominant water consuming sectors in the catchment?
- ✓ How much blue and green water required for crop production in the catchment?
- ✓ Can the water resources of Lake Hawassa catchment fulfill existing water demands of all water users?

1.5. Scope of the study

The scope of this research is limited to quantifying blue and green water resources and consumption share of water use sectors. It didn't encompass the evaluation of irrigation efficiency, small scale irrigations and ground water potential.

General scope of this research covers the following:

- ✓ Quantification of the total surface water resource potential within the catchment using rainfall-run-off model.
- ✓ Estimation of water consumption amount for different water use sectors.
- ✓ Identification of data quality and recommendations on future monitoring requirements.

1.6. Significance of the research

This study focuses on the determination of total available water resource in quantity manner and dominant water use sectors in the catchment which will have a paramount importance to understand the better picture of water resources.

Knowing the magnitude of the available water resources is the most important step towards proper management and optimum use of the available fresh water resources, therefore the output of this study can be used as an input for decision support for water resources planning, development, and management of water resources in the catchment.

2. LITERATURE REVIEW

2.1. Water resource potential in Ethiopia

Ethiopia is naturally endowed with abundant water resources that help to fulfill domestic requirements, irrigation and hydropower. The overall land mass of the country is hydrologically divided into twelve basins, eight of these are River Basins, one Lake Basin and three Dry Basins. The country has also 12 major lakes which have enough potential to use for different purposes (Mohamed et al., 2013).

The total mean annual flow from all the 12 river basins is estimated to be 124.25 BCM and groundwater potential is estimated to be 30 million cubic meter. The total area covered by these basins is 1.13 Million square kilometers (Mkm^2) of which 99.3 percent is a land area and the remaining 0.7 percent is covered with water bodies. The water bodies that include lakes, rivers, reservoirs, small water bodies, swamps and flood plains (Ayalew, 2018).

The distribution and quantity of water has strong relationship with the topography and rainfall distribution. All parts of the country are not getting equally amount of rain fall. The highest mean annual rainfall (more than 2700 mm) occurs in the southwestern highlands, and then it gradually decreases in the north (to less than 200 mm), northeast (to less than 100 mm), and southeast (to less than 200 mm) (World Bank, 2006).

All major river basins in Ethiopia have an integrated development master plan study, and their potential in terms of economic development be known (MOWR, 2002). Currently, there are great efforts towards developments in some river basins for energy generation and large scale irrigation projects to sell power to neighboring countries and attain food self-sufficiency, respectively. To utilize this huge amount of water in a sustainable manner, it is necessary to understand the quantity and quality in space and time through studies and researches.

2.2. Overview of Water Balance studies in Ethiopia

Various studies have been conducted in Ethiopia to study the water balance of basin. Some of the findings of the studies are discussed below:

Wale et al., (2009) developed hydrological water balance of Lake Tana Upper Blue Nile basin. The study aimed to establish the Lake Tana water balance on a daily base by estimating of lake rainfall, rate of evaporation and runoff from gauged and ungauged catchments by rainfall runoff modeling. The study showed that runoff from ungauged catchment as the most uncertain component of Lake Tana water balance and estimated by transferring model parameters from gauged catchments using a regionalization procedure, spatial proximity procedure and catchment area ratio method. The author concluded that Lake Tana water balance highly sensitive to Lake Basin rainfall and river inflow.

Shawul et al., (2013) estimated the water balance components of Shaya mountainous watershed, Southeastern Ethiopia. The objective of this study was to perform calibration and validation of SWAT model at the outlet of Shaya watershed in the Bale Mountainous area and to estimate water balance components of the watershed. The study determined the water balance components and concluded that actual evapotranspiration contributed a larger amount of water loss from the watershed. Woldeyohannes, (2016) also estimated the monthly, annual runoff yield and water balance components of Tegona watershed in south eastern Ethiopia using SWAT model. This study recommended that SWAT model can be a potential tool for simulation of stream flow and water balance components of ungauged watershed in the highlands of Ethiopia with similar hydro-meteorological characteristics to Tegona watershed.

Alamirew et al., (2004) developed a water balance model of lake Ziway watershed. The objective of the study was to understand the hydrology of lake Ziway. Evapotranspiration was estimated using Modified Penman Method and was compared with the data from evaporation pan. Average rainfall for the area was estimated using Isohyetal Method. The model was developed using the values from each water balance component. Besides analysis of the river flow data from gauging station at Meki town was made and the result has shown that the river will actually dry up at some time during the period December to March. From analysis the study conclude that 85 % of the water coming to lake Ziway goes as evaporation and recommended to look for a technology that could be economically used to reduce evaporation and make available the water for irrigation and other uses

Desta & Lemma, (2017) determined the water balance components of Lake Ziway watershed. The study aimed at quantifying and comparing water balance components, feeder rivers’ discharge and evapotranspiration (ET) in the study region using SWAT (Soil and Water Assessment Tool) model. The authors concluded that a decrease of surface and base flow and an increase of evapotranspiration are observed in Lake Ziway sub-watersheds including the lake itself.

2.3. Water balance of Lake Hawassa catchment

Recent studies focused on the Lake Hawassa catchment water balance include; Gebreegiziabher, (2004), Ayenew et al. (2004), Ayenew and Gebreegiziabher (2006), AG Consults (2007), and WWDSE (2011) are conducted on the catchment. Brief explanations about some of these studies are given below.

Gebreegziabher (2004) conducted a water balance study at a watershed level. This study conducted using the Thornthwaite and Mather soil water balance procedure and spreadsheet model for the period of 1981-1998. The result of the catchment water balance showed that long-term mean annual values of rainfall, actual evapotranspiration, and catchment runoff constitute 1398, 916 and 482 Mm3 respectively.

In this study, catchment runoff for different scenarios compared with that of 1998 land use condition and reported a Change of 22% and 4% for the 1965 and 2004 land use situations, respectively. In accordance, he concluded, 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 (Gebreegziabher, 2004).

Dijk (2016) studied the hydrology of Lake Hawassa catchment. The main goal of the research was to quantify the water balance of the Lake Hawassa catchment area in relation to land use. The study used the Soil and Water Assessment Tool (SWAT). The author concluded that the discharge increase of the Wosha and Tikur Wuha streams are most likely related to land use changes within the Tikur Wuha sub catchment.

2.4. Land use land cover change of Lake Hawassa catchment

A number of studies were performed in Lake Hawassa catchment in relation to the impact of land use/ cover change on the local water cycle.

The study of AG Consult (2007) indicated that there were high land cover changes in the past 30 years. Accordingly, it presented the rate of change between 2000 and 2005 with the highest being 91% and 81% for Urban and shrub land respectively, followed by 33% and 31% for woody grass and dense shrub in that order, similarly a 26% for both open forest and bare land. The Water body area (that includes Lake Hawassa and Lake Cheleleka) has remained almost constant in its total area coverage, i.e. 100.78, 102.34 and 99.59 km^2 for the years 1976, 2000 and 2005 respectively. As per the study, when the two lakes area separately analyzed, Lake Hawassa showed a slight rate of increase, which is almost 9 %, while Lake Cheleleka significantly decreased by about 75% in the last 30 years. Urban Built-up area has been increased by 202 % in the same period while Marsh area has progressively declined in the three periods to cumulative rate of greater than 39%.

Wondrade et al. (2014) conducted another important study in land use land cover change of Lake Hawassa catchment. According to this study nine land use land cover types were identified. These were Water, built-up area, crop land, woody vegetation, forest, grassland, swamp, bare land, and shrub. The study produced the thematic maps of the year 1973, 1985, 1995, and 2011. The dominant land cover class was found to be cropland, which accounted for 43.6% in 1973 and increased to 56.4% in 2011. Woody vegetation and forests, which covered 21.0% and 10.3% of the area in 1973, respectively, diminished to 13.6 and 5.6% in 2011. The other land LULC types, water, built-up, grassland, swamp, bare land, and shrub covers 7.2%, 0.3%, 5.0%, 4.2%, 1.26%, 6.6% in 1973 and 6.7%, 1.7%, 4.6%, 4.5%, 2.9%, 4.2% in 2011 respectively. The result of the study showed that cropland, woody vegetation, and forest had the highest magnitude of change from 1973 to 2011. Wetlands were identified as the most affected landscape feature. Lake Chelelka as part of the wetland, which covers about 11.3 Km^2 in 1973, had totally vanished in 2011.

2.5. Hawassa Lake level rise

Lake Hawassa is one of the nine lakes with in the central rift valley system which serves for wide range of socio-economic activity. Deferent water use sectors are recently increasing their pressure on the water balance of Lake Hawassa which is recharged by precipitation and one perennial river namely Tikur Wuha River (Ayenew, 2007).

There are many attempts have been made to investigate, quantify and provide information regarding the dynamic water balance of the lake. The earliest available studies on Lake Hawassa Level Rise study was carried out by Water Works Design and Supervision Enterprise for the period 1970-1998 (WWDSE, 2001). The major purpose of the study was to investigate the causes of lake level rise, to forecast future conditions of lake level rise, and to propose remedial measures that could curb the situation in the short-term and long term plans.

According to the study report by WWDSE (2001), the lake catchment area including the surface area of the lake is about 1440 km^2 and the lake surface area based on 1:10,000 scale topographic map was about 100 km^2. Thus, the effective catchment area of the lake is about 1340 km2. The surface area of Lake Hawassa occupies about 7% of the total lake catchment area. The town of Hawassa lies in an area of about 1% of the total lake catchment area. The relatively compacted surface of the Hawassa town and the roof catchments have resulted in generating higher magnitude of runoff and associated with it, the problem of drainage in the urban area founded along the shoreline of Lake Hawassa. This study used the historical records of over-lake rainfall, stream flow, surface runoff (using a runoff coefficient of 0.13 and 0.19) and evaporation (using pan coefficient of 0.8) together with the observed lake storage (as computed from change in lake level) to estimate the ground water flow component as the residual of the balance. The estimated magnitude of net ground out flow was 71 $x10^6$ m^3**.**

According to the bathymetric survey carried out by WWDSE, (2001) showed that deepest point of Lake Hawassa measures about 21m below the surface water level. In addition the survey was carried out to produce bathymetric map of the lake and to develop depth- area as well as depth-volume curves of the natural lake reservoir. The bathymetric map of the lake with a scale of 1:10,000 and contour interval of 2m was prepared. From this map, the area-capacity-elevation curves of the lake were made and used for computing change in storage.

Based on the results of the bathymetric survey WWDSE (2001), it was concluded that the 1998/1999 surface area of Lake Hawassa was about 100 km^2 and that of Lake Cheleleka was practically zero. About 30 years back from 2001, the surface area of Lake Hawassa and Lake Cheleleka were about 88 km^2 and 12km^2 respectively. The transformation of Lake Cheleleka to swampy area has dramatically resulted in the complete depletion of its regulating capacity, which in natural condition controlled the surface runoff since its existence as lake. Accordingly, the expansion of Lake Hawassa by an equal magnitude (about 12 km^2) to that of the surface area of Lake Cheleleka 30 years ago clearly shows the disappearance of Lake Cheleleka and rise in the level of Lake Hawassa in recent years.

Gebreegziabher, (2004) also studies the water balance of the Lake using spreadsheet model for the period of 1981-1998. The study quantified the water balance components of the Lake Hawassa on monthly bases and assess if the lake level rise could be attributed to natural or anthropogenic factors. **T**he simulation results of the Lake water balance showed that evaporation, rainfall, surface runoff, and constant ground water outflow from the lake constitutes 131, 106, 83 and 43 Mm^3 of the annual average water balance respectively.

Another important study was performed by Belete et al., (2017) to investigate dramatically rise of the lake level without falling back to the original. The main findings in this study are that the general variability in the lake level and its resultant rise has significant linkage to the temperature variability at the Pacific Ocean. The lake level tends to be high during El Niño and low during La Niña episodes. The typical examples were showed the coincidence of extreme historical maximum lake level to the strongest El Niño event of the century that occurred in 1997/98 and the lowest lake level record in the year 1975 with a strong La Niña year. The coincidence of climate regime shift in the Pacific Ocean in 1976/77 with an equivalent regime shift in the lake level is an additional confirmation for the possible climate-hydrology linkage (Belete et al., 2017).

In this study, the highest peak was observed in November 1998 (22.54 m) followed by October and December of the same year (22.49 m each). The lowest level in this year was observed in June (21.8 m) which was greater than 92.5% of historical records. This particular year was known for its peak records in many parts of the world. The general suggestion of this study was water level fluctuations of closed lakes are considered as meaningful indicators of climatic changes (Belete et al., 2017).

Still with the number of studies and their importance, the cause of lake level rise has not been concluded and not yet explicitly investigated. All the above reviewed studies indicate that sharp raises in water level of Lake Hawassa had been occurred and that could not be explained in terms of the water balance components. They explained the existence of divergence between the observed and simulated lake as it could be the effect of neotectonic activities, which in turn possibly affect the ground water flow regime. They also suggested the need for detailed investigation of hydro-climatic variables for better efficiency of the water balance model.

2.6. Blue and Green Water

Freshwater is a renewable resource that is naturally replenished over time when moving through the hydrological cycle. Precipitation forms the input of freshwater on land. Subsequently, it takes the blue or the green pathway back to the ocean and atmosphere before eventually returning as precipitation again. The water that runs off to the ocean via rivers and groundwater is called the blue water flow. The green water flow is formed by the water that is temporarily stored in the soil and on top of vegetation and returns to the atmosphere as evaporation instead of running off (Schyns et al., 2015).

Falkenmark and Rockström (2004) initiated a paradigm shift in water resource management by proposing to change the traditional notion of the freshwater source from rivers, reservoirs, and aquifers to precipitation. In their description of water resources, precipitation is partitioned at the soil surface into blue water (as surface or groundwater) and green water (as soil moisture regenerated by precipitation); typically absent in water management considerations (Falkenmark and Rockström, 2004, 2006).

There have been many studies quantifying the green and blue water resources since the advent of the concept. For instance, Gerten *et al.* (2005) and Rost *et al.* (2008) used the LPJ/LPJmL model to estimate global green and blue water consumption over the past 30 years. Schuol *et al.* (2008) and Faramarzi *et al.* (2009) adopted the SWAT model to simulate blue and green water resources in Africa and Iran, respectively. Liu *et al.* (2009) quantified the effect of land use and land cover changes on green water and blue water in the northern part of China. Zeng *et al.* (2012) simulated spatial and temporal patterns of both blue and green water flows by the SWAT model for the Heihe River basin.

Research on water scarcity has mainly focused on blue water (ground and surface water), but green water (soil moisture returning to the atmosphere through evaporation) is scarce, because its availability is limited and there are competing demands for green water. Crop production, grazing lands, forestry and terrestrial ecosystems are all sustained by green water (Schyns et al., 2015).

Consumptive uses are different from water withdrawals in that withdrawals can be returned to the blue water cycle, whereas consumptive uses cannot (Rockström *et al.*, 2010). Blue water consumptive uses include some fraction of drinking water, evaporative losses through cropland irrigation or hydropower, and incorporation of water into products. Green water consumptive uses exclusively occur through ET with a distinction between productive and unproductive vapor flows characterized respectively by transpiration and direct evaporation of soil moisture (Falkenmark and Rockström, 2006). Total freshwater withdrawal is the volume of freshwater extracted from its source (rivers, lakes, aquifers) for all economic activities.

A mind-shift is necessary regarding the way we think about water and agriculture, instead of a narrow focus on utilization of blue water (surface water and groundwater). It is important to be aware that precipitation is the ultimate source of water that can be managed. There is high potential to improve the use and management of rainwater in the catchment (Brandsma et al., 2013).

Up to now, studies of freshwater availability have predominantly focused on the quantification of the blue water, while ignoring the green water as part of the water resource and its great importance especially for rainfed agriculture (White et al., 2009).

2.7. Virtual water

Virtual water, understood as the volume of water needed to produce a good or service, in the context of trade among countries, allows assessing the relative dependency of different countries on imported virtual water (Montesinos et al., 2011). The assessment of virtual water flows in virtual water trade studies is generally carried out at the national level, thus concealing the spatial variability of many countries that comprise a wide range of agro-climatic areas. A finer spatial resolution is needed to apply the virtual water concept with a view to improving local water resources management at the regional or basin scale.

Virtual water content includes both blue and green water, with blue water as the most 'manageable' component, leaving considerations of green water efficiency often overlooked (Aldaya et al., 2009; Falkenmark and Rockstrom 2004).

The enormous dependency of agriculture, and consequently food production, on water resources poses a problem regarding the assignment of scarce resources, especially in certain areas of the world where water scarcity affects food security. In these areas (arid and semiarid countries), VW trade can alleviate water scarcity by importing high water consuming products from countries with abundant water resources. In this way, these countries can supply food to their populations and allocate their scarce resources to other primary uses such as domestic use. The main goal of the majority of VW studies is to achieve food security for these countries by assessing VW trade pathways between countries (Montesinos et al., 2011).

Initial quantification of virtual water was done for crops Hoekstra and Hung, (2002), and for livestock and livestock products Chapagain and Hoekstra, (2011) by calculating the global virtual water trade of products in volumes of water per year and country. Virtual water (VW) of crops is calculated by using methods outlined in the FAO Drainage Paper No. 56 (Starr & Levison, 2014).

Chapagain and Hoekstra (2008) carried out a VW balance in the world from 1997 to 2001. They concluded that, on average, 991.25 billion m^3/year of international VW transfers are related to crops and crop products (61% of total amount), 276.25 billion m^3/year to livestock products (17%) and the remaining 22% to industrial products (357.5 billion m^3/year). These figures are consistent with the role of agriculture as the largest water user worldwide (over 80% of total global water withdrawals). For this reason, the concept of VW has been developed to assess the water requirements for agricultural production (Montesinos et al., 2011).

Incorporating virtual water into a water budget, rather than using general consumptive factors, can provide crop-specific consumption rates, identification of blue and green water use, and distinction of virtual blue water sources (Starr & Levison, 2014).

When considering water management and water stress, it is important to understand how much water, blue or green, is consumed during the production of crops either through evapotranspiration or commodity exportation (Starr & Levison, 2014).

The benefits of calculating VW consumption at a watershed scale include increased precision of input data, application to specific commodities, and detailed information for landuse choices.

2.8. Water consumptions

Water demand is defined as the volume of water required by users to satisfy their needs. Demand is the theoretical while consumption is actual. The demand of water is determined by social, economic and environmental needs (number of households, hectares of irrigated area and crop types, minimum stream flow, etc.) and the water use rate of each activity.

It is usual to classify water demand in various sorts depending on the characteristics of the consumers. The most common types are domestic, non-domestic (commercial, institutional), industrial, firefighting and unaccounted water demand. Domestic demand includes the water required in private building for drinking, cooking, bathing, flushing and washing clothes. The domestic consumption varies according to the living conditions of the consumers, economic status of the community, climatic condition, mode of service and affordability and accessibility of the service. Domestic demand may reach 350 l/c/day in developed world and 50 to 120 l/c/day developing countries (Larry, 2010). Non -domestic demand comprises Industrial, Commercial, Institutional, Firefighting demands and unaccounted water demand, Industrial water demand represents the amounts of water demand required by industries and factories in the cities.

The existing imbalance of water availability and water consumption causes water scarcity to be one of the most pressing environmental issues in the world today. Water demand is defined here as the volume of water required by users to satisfy their needs. Surface fresh water is the most readily available resource to meet the water demand of agriculture (i.e., irrigation and livestock), industry, households and municipalities.

There is an increasing in population growth in our country; the country is also in a range of fast growing countries; the government has a plan to emerge middle income country with in short period of time. Due to this reason the water demand pattern of the country will be changed in the future. Therefore it is necessary to study the country's current as well as future water potential and its demand in order to manage the water resource potential.

2.8.1. Agricultural water consumption

Agriculture is an important activity thought the world in terms of food security, economic activity and water use. Irrigated agriculture, moreover, plays a disproportionately important role because it is generally two to three times more productive than rain-fed agriculture.

As the largest water consumer world-wide, the agriculture sector has become a primary issue for water resources management. In regions where increasing development and population growth is demanding expansion of agriculture, large water withdrawals are required especially in arid and semi-arid locations. Irrigation is agro-economically beneficial by increasing soil productivity, extending growing seasons and enabling choice in crop types. However, in many locations, there is little documentation of actual agricultural water use, with the highest unknowns for groundwater abstraction (Zoumides et al., 2013).

To investigate agricultural water consumption at a catchment scale, consumption sources must be further distinguished between blue and green water. As agricultural production is the single largest water user in most of the areas of the world, it is especially important to have a spatially explicit assessment of both green and blue water uses in agriculture (Allan, 1994).

Green water resource has been generally used to refer to the water that comes from precipitation, is stored in the soil, and subsequently released to the atmosphere through crop evaporation. In contrast, blue water refers to the water in rivers, lakes, reservoirs, ponds and aquifers. Both green and blue water resources are important for food production. Rainfed agriculture uses green water only, while irrigated agriculture uses both green and blue water (Falkenmark, 1995).

Green water of a crop was taken equal to the lower of either the effective rainfall or the crop water requirement, and blue water was equal to the irrigation water used(Starr & Levison, 2014).

Field measurements of water use by crops are complex, time consuming and expensive. Generally a crop water requirement is estimated from empirical equations. In order to carry out a detailed estimate of crop water use using empirical formulae, the following information is required:

- Reference crop evapotranspiration;
- Crop type and crop evapotranspiration;
- Cropped area;
- Effective rainfall;
- Soil type and leaching requirements;

The FAO recommends the Penman-Monteith method as the standard method for the computation of ETO. The use of the Penman-Monteith method does require a reasonable quantity of climatic data. However, advice on the infilling of missing data and the setting up of climate stations data is given in FAO (FAO, 1998).

There are also a number of software packages that use the Penman-Monteith method equation to assess reference crop evaporation. The FAO computer program CROPWAT 8.0 utilizes the Penman-Monteith method and a spreadsheet is also available from the FAO to calculate reference crop evaporation. This method is recommended for use wherever possible, providing there is sufficient meteorological data (FAO, 1992).

It should be noted that often the greatest uncertainty in determining irrigation water use is the estimation of irrigation efficiency. The overall irrigation efficiency is defined as the ratio of water consumed by crops to the water diverted from the source. The overall irrigation efficiency can vary from 10% to 90% and is heavily dependent on the irrigation technology used, and the operation and maintenance of the irrigation scheme.

Irrigation water consumption is a function of acreage, crop type, growing cycles (and their corresponding crop coefficients), reference evapotranspiration, and effective precipitation within the irrigated area.

2.8.2. Livestock water consumption

Livestock are major components of the livelihoods of both pastoralists in the arid and semi-arid lowlands of the country, and the crop–livestock farmers in the highlands. Ethiopia is home to about 35 million tropical livestock unit (TLU), and on average, one TLU requires about 25 litres of water per day. Water resource is pertinent and vital for the existence and development of the livestock sector. Tropical livestock unit is equivalent to an animal of 250 kg live weight on maintenance (Seleshi, 2010).

Consumptive water use in livestock are generally divided into two categories (Ylva, 2010)

- Drinking and process water :- direct blue water use
- Water use for production of feed, fodder and grazing :- blue and green water use

There are three sources of water for the animal: (1) drinking water (2) water contained in feeds and (3) metabolic water. Water contained in feeds consumed (preformed water) is highly variable from feed to feed according to the moisture content, which can range from as low as 5% in dry feeds to as high as 90% or more in succulent feeds (Seleshi, 2010).

One kilogram of grain used in livestock feed requires about 1000 to 2000 kg of water if the feed is grown in the Netherlands or Canada. The same grain will, however, require approximately 3000 to 5000 kg of water if grown in an arid region like Egypt or Israel. That difference in water requirement will have an impact on the total water use for a specific product relying on the grain from a particular region. Livestock in itself contains between 5 and 20 times more virtual water per kg product than crop products (Chapagain & Hoekstra, 2003).

Livestock production requires high amounts of water. The water requirements of livestock are influenced by several factors such as type of animal, its activity, feed intake and diet, quality of available water, temperature of water and temperature of the ambient environment (Lardy et al., 2008).

Water contributes up to 80% of an animal's body weight. Deprivation of water more than any other nutrient quickly leads to reduced feed intake, production, reproduction, poor health, and death. Water requirement depends upon the Type of animal, size of animal, feed and salt ingested, lactation, and ambient temperature and an animal's genetic adaptation to its environment (Markwick, 2002).

The water requirement of domestic animals varies between species, between breeds or varieties within species and between individuals within breeds. For example, heavy western breed cows have a higher water intake (60 to 90 liters/day) than zebu cows (25 liters/day with 350 kg live weight. The water demands of sheep, goats and camels are not as high as those of cattle. Water requirement increases with growth, and with increases in productive processes such as lactation and egg laying. Water requirements also largely vary according to other factors such as food intake, quality of the food and air and water temperature. As the demand of the individual animal for water is variable, only average estimates of water requirements in a specific climatic environment are generally indicated (Seleshi, 2010). Water intake of different class of animal are listed in table 2.1.

Table 2-1: Water intake of different class of animals (Seleshi, 2010)

Class of livestock	Litres Per day
Beef cows	15-40
Dairy cows	25-50
Horses	15-40
Pigs	10 -30
Sheep and goats	5-6
Chickens	(25 - 30)/100 birds
Turkeys	(65 - 70)/100 birds

Note: Extremely hot season weather could increase the high values another 20%-30%

2.8.3. Urban water demand

The primary functions of urban water management include meeting hygiene (supply and sanitation), drinking water, drainage, urban agriculture, and recreational needs. Meeting these needs while protecting natural resources and human health, especially if water is scarce, is key to sustainable development (Russo et al., 2014).

The water furnished to a city can be classified according to its ultimate use or end. The uses are: Domestic, Commercial & Industrial, Public use and Loss and waste.

Urban domestic water demand:-Urban domestic water demand includes water furnished to houses, hotels, etc, for sanitary, culinary, drinking, washing, batching, and other purposes

To satisfy the basic human needs like drinking, washing and cooking a minimum of about 25 litres water per day and person is estimated for private households .Water use in households varies enormously between different regions: while around 20 litres per capita per day are used in Africa, an US – American has in average a water demand of almost 300 litres per day (Scheele and Malz, 2007)

The amount of domestic water consumption per person varies according to the living standards of the consumers. The domestic consumption may be expected to be about 50% of the total in the average city, but where the total consumption in small, the proportion will be much greater.

Commercial and industrial:-Water so classified is that furnished to industrial and commercial plants. Its importance depends up on local conditions, such as the existence of large industries and whether or not the industries patronize (utilize) the public water works. Self-supplied industrial water requirements are estimated to be more than 20 percent of municipal water supply demand (Wallingford, 2003).

Urban industries tend to be metered, usually according to the volume of water used, through an average charge or a variable marginal charge based on block rates. Where larger commercial and industrial users tend to be metered, determining demands can be facilitated through analyzing meter records. Alternatively, they may have their own source, especially if they are outside urban centers. Monitoring records may exist or there may be some indication as to the energy consumption of pumps or other references to demand and use.

The quantity of water required for commercial and industrial purposes can be related to such factors as number of employees, floor area of the establishment, or units produced.

Public Use:-The quantity of water required for public utility purposes Includes water for public institutions like schools, watering of public parks, washing and sprinkling of roads, use of public fountains, clearing wastewater conveyance, etc. Usually the demand may range from 2-5% of the total demand. Water use rate of some public institutions are given in table 2.2.

Table 2-2: Water use rate of some public institutions (Wallingford, 2003)

Category	Typical rate of water use per day
Day schools	5 l/pupil
Boarding schools	50 l/pupil
Hospitals	100 l/bed
Hostels	80 l/bed
Mosques	5 l/visitor
Cinema houses	5 l/visitor
Offices	5 l/person
Public baths	100 l/visitor
Hotels	100 l/bed
Restaurant/Bar	10 l/seat
Camp	60 l/person
Prison	30 l/person

Losses and Waste:-Water lost or unaccounted for because of leaks in main and appurtenances, faulty meters, and unauthorized water connections and should be taken in to account while estimating the total requirements. Losses and leakage may reach as high as 35% of the total consumption(Engdaw, 2016).

This water is sometimes classified as "un accounted for", although some of the loss and waste may be accounted for in the sense that its cause and amount are approximately known. Water losses are normally calculated as a percentage of the sum of the domestic demand. Unaccounted water levels are the difference between the total quantities of water abstracted and the quantity of water consumed(Engdaw, 2016).

2.8.4. Rural domestic water demand

According to Engdaw, (2016) estimating domestic water demand and use at a catchment level for rural areas in Ethiopia is problematic owing to the lack of measured data available. Estimates of rural domestic water demand and use are further complicated by the lack of definitions of the terms used. Hence in the context of assessing rural water demand and use it is important that various terms are clarified.

In general estimation of rural water demand and use is difficult because:

- The majority of rural domestic water supply systems are unmetered;
- Data concerning domestic rural water demand and use is often expensive and time consuming to collect;
- The level of service provided by the water supply system is often unknown.

Rural water demand encompasses all domestic-type water requirements outside of urban areas. The first term accounts for the domestic water use (including also subsistence irrigation and other economic activities and computed as the product of the population times a per capita usage) and a second term to account for the livestock watering (computed as the product of the number of livestock times a per capita usage).

Many water supply schemes in rural areas are fairly basic; however, the patterns of use and demand are more complicated and tend to be dependent on many factors. Such factors include: Population, Household occupancy rate, Level of service of the water supply for each household, Tariff levels, Willingness and ability to pay, Local knowledge and indigenous practices, Cultural values, traditions and religious beliefs, Climate and Water quality.

World health organization (WHO) recommends 50–100 l of water per capita per day (l/c/day) to meet domestic needs such as personal hygiene, washing and cleaning (Howard and Bartram, 2003).

2.8.5. Industrial water consumption

Industrial water consumption includes water used for various purposes: as a part of the final product, for the maintenance of manufacturing processes (cleaning, flushing, sterilization, conveying, cooling, etc) and for the personal needs (usually comparatively marginal). The total quantity is largely depending on the type of industry and technological process.

Industrial withdrawals provide water for such purposes as fabricating, processing, washing, diluting, cooling, or transporting a product; incorporating water into a product; or for sanitation needs within the manufacturing facility. Some industries that use large amounts of water produce such commodities as food, paper, chemicals, refined petroleum, or primary metals. Water for industrial use may be delivered from a public supplier or be self-supplied (Dieter et al., 2018).

There is a clear distinction between the terms industrial water use and industrial water consumption. Industrial water use is defined as the quantity of water that is abstracted from a source (e.g. a river or borehole) for use by an industrial plant. In many industrial processes significant quantities of the water that is abstracted can be re-cycled and re-used. Industrial water consumption is the quantity of water that is "lost" (e.g. by being incorporated in a product such as soft drinks, or through evaporation from cooling towers) during the manufacture of a particular product. The tables 2.3 provide details of specific water consumption in terms of volume of water consumed per unit of product produced.

Table 2-3: Industrial water consumption (Adapted from: HR Wallingford, 2003)

Industry	Litres per unit product
Carbonated soft drinks	1.5-5 per litre
Fruit juices	3-15 per litre
Beer	4-22 per litre
Wine	1-4 per litre
Fresh meat (red)	1.5-9 per litre
Bricks	15-30 per kg
Cement	4 per kg
Polyethylene	2.5-10 per kg
Paper	4-35 per kg
Textiles	100-300 per kg
Cars	2500-8000 per car

The industrial sector uses about 20% of global freshwater withdrawals. This includes water for hydro and nuclear power generation, industrial processes and thermal power generation. One of the major challenges for industry today is to effectively address the unsustainable exploitation and contamination of freshwater resources around the world. In comparison to other sectors, industry uses relatively little water on a global scale (20%of total freshwater withdrawals). Still, the annual quantity of water used by industry is rising and industry will increasingly be competing over limited water resources with growing urban and agricultural water demands (UN-WDPAC, 2010).

Expanding the industrial sector is critical for poverty alleviation, delivery of goods and services, job creation, and improving standards of living; especially in developing countries. However, in many countries industrial development goes hand in hand with environmental degradation and resource depletion, which threaten opportunities for sustainable economic growth. In low-income countries industry accounts for about 5% of water withdrawals, compared to up to 86% in some high income countries such as Germany (UN-WDPAC, 2010).

2.8.6. Environmental flow water demand

The Brisbane Declaration (2007) defines environmental flows as quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.

The environment is increasingly being considered a legitimate water user in many world countries. As a consequence the water requirement of the environment needs to be estimated.

The amount of water that will be allocated to the environment is a decision made by society, and is to some extent arbitrary. The quantity of water allocated to the environment will always be less than what the environment ideally would require, namely the natural, undisturbed, flow regime of a river. Society, therefore has to weight the potential costs and benefits to the environment and to all other water users, of allocating (or not) a certain amount of water to the environment. In so doing, society accepts a certain modification of the natural environment. This accepted level of modification may differ from river to river, and is sometimes defined in terms of "ecological management classes". Environmental flow recommendations represent the flow requirements intended to keep the ecosystem health at an acceptable level (Acreman and Dunbar, 2004)

Water supply planners are proactively addressing the water needs of aquatic ecosystems by reserving environmental flows for ecosystems to prevent ecological damage (Richter et al., 2006). The environmental or in stream flow requirement is often defined as how much of the original flow regime of a river should continue to flow down it in order to maintain the river ecosystem in a prescribed state. However, an environmental in stream flow often fulfils a number of different functions.

Despite the simplicity of the concept, difficulties arise in the actual estimation of EF values. This is primarily due to the inherent lack of both the understanding of and quantitative data on relationships between river flows and multiple components of river ecology.

There is a range of methods available for assessing in stream flow requirements based on:

- Simple hydrological indices;
- Hydrological simulations;
- Consensus and discussion based approaches;
- Historical data analysis;
- Biological response simulation techniques often referred to as habitat simulation methods.

Hydrological index methods are the simplest type of environmental flow assessment, least data intense and rely on the use of historical hydrological data for making flow recommendations. These data are usually in the form of long-term, historical monthly or daily discharge records. In flow duration curve analysis naturalized or present-day historical flow records are analyzed over specific durations to produce curves displaying the relationship between the range of discharges and the percentage of time each of them is equaled or exceeded.

2.9. Hydrological model

Hydrological 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 (Munyaneza et al., 2013). Hydrological models are mathematical formulations to determine the runoff signal which leaves the watershed from the rainfall signal received by the basin. Modeling of the rainfall runoff processes of hydrology is needed for many different reasons the main reasons being limited range of hydrological measurement techniques and limited range of measurements in space and time (Beven,1985). However, the applications of those models are highly dependent on the purposes for which the modeling is made.

Oyebande (2001) reported that the main challenge associated with applying successfully rainfall-runoff model lies in the lack of monitoring data, mainly rainfall spatial distribution over the catchment area, since rainfall is the primary input in any hydrological model. Another potential problem is having no reliable flow data that can lead to reliable calibration and validation of catchment parameters.

The process of transformation of rainfall into runoff over a catchment is very complex, highly nonlinear, and exhibits both temporal and spatial variability (ASCE, 2000). To select a model for determining the quantity of surface runoff that takes place in a catchment it is necessary to understanding the complex relationships between rainfall and runoff processes, which highly depends upon many geomorphologic and climatic factors.

Either infiltration or saturation-excess runoff generation processes may pre - dominate temporarily and spatially within a catchment. Infiltration excess or Hortonian flow occurs when rainfall intensities exceed the rate at which water can infiltrate into the soil (Kumar et al., 2016).

Hortonian flow is primarily controlled by soil type, land cover and rainfall intensity whereas the saturation excess runoff is generated by direct precipitation on or exfiltration from saturated areas in the catchment (Kumar et al., 2016).

In many regions runoff is most commonly generated on relatively small portions of the landscape that are susceptible to becoming completely saturated. Ones the soils in these areas saturate to the surface, any additional rainfall that falls (irrespective of intensity) becomes overland flow. This process is termed as saturation excess overland flow.

Liu et al. (2009) shows that the runoff in most of the Ethiopian highlands is due to saturation excess flow. Saturation excess flow is one mechanism for runoff generation in areas with shallow soils characterized by a highly conductive top soil underlain by a dense top soil, and in regions where the ground water is close to the surface. Runoff is usually generated from areas that are saturated or become saturated during a storm

Most commonly used models in predicting surface runoff are Soil and Water Assessment Tool (SWAT) (Arnold et al. 1993), General Watershed Loading Function (GWLF) (Haith and Shoemaker 1987), and Agricultural Non-point Source Pollution (AGNPS) (Young et al. 1989),

Majority of the research used SWAT-CN in Ethiopia (e.g. Setegne, 2008; Shiferaw et al., 2016; Halefom et al., 2018). This model assumed an infiltration excess (Hortonian) overland flow generation mechanism following Soil Conservation Service Curve Number (SCS-CN) (USDA-SCS, 1972) method. This model does not account variable source area (VSAs) of runoff generation.

However, few studies used SWAT-WB to model spatial distribution of saturation-excess runoff from VSAs within the catchments (e.g. Liu et al. 2008; Collick et al. 2009; Steenhuis et al., 2009)..

2.10. SWAT-WB model

Hydrological models can provide more insights into the mechanisms of land surface and hydrological processes, and are regarded as a powerful tool for simulating hydrological processes and assessing water resources spatiotemporally. The SWAT model is one that can be applied to large catchments for quantitatively determining the spatiotemporal variation of water resources (zongxue & depeng ., 2014).

SWAT is a process-based and time continuous hydrological model operating at 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. Further technical details on the model are given by Neitsch *et al.* (2005).

The soil water balance equation is the basis of hydrological modeling. The simulated processes include surface runoff, infiltration, evaporation, plant water uptake, lateral flow and percolation to shallow and deep aquifers. In this thesis surface runoff is estimated by saturation-excess processes.

SWAT-WB is a modified version of the Soil & Water Assessment Tool, which was developed with the explicit goal of accurately modeling surface runoff generation without using the USDA-NRCS Curve Number (CN) method. Instead of using the CN method, a physically based soil water balance (WB is short for water balance) is used for every day of simulation. These results in a version of SWAT which models runoff generated strictly from saturation-excess processes; no surface runoff will be generated with SWAT-WB until the soil becomes sufficiently saturated (White et al., 2009).

2.11. Calibrating SWAT-WB

Distributed watershed models are increasingly being used to support decisions about alternative management strategies in the areas of land use change, climate change, and pollution control and water allocation. For this reason it is important that these models pass through a careful calibration and uncertainty analysis.

The prediction uncertainty of model is reduced by elaborating on finding a better parametric model according to local conditions in the calibration step. Model calibration is carried out as model predictions are compared with the observed data. The process is continued to find acceptable prediction model output according to measured data while changing model input parameter values. When there are many uncertainties in the model and complicated hydrologic models are generated, manual calibration can take a long time (Balascio et al., 1998).

There are semi-automated or automated calibration methods which can be easily used to calibrate SWAT. Dynamically Dimensioned Search (DDS) Algorithm is an autocalibration routine developed by Dr. Bryan Tolson (University of Waterloo) and Dr. Christine Shoemaker (Cornell University), primarily for use in watershed models. This algorithm is used outside of the GIS interface and can be downloaded in various formats (White et al., 2009).

PARASOL is also an autocalibration algorithm included in the SWAT program and available for use within the GIS interface also can be used to calibrate SWAT-WB. Using PARASOL requires the user to make some important adjustments to replace the original SWAT program to SWAT-WB program (White et al., 2009).

SWAT-CUP is a public domain program and it is an interface that was developed for SWAT. Using this generic interface, any calibration, uncertainty or sensitivity program can easily be linked to SWAT. The program links Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol), Sequential Uncertainty Fitting (SUFI2) and Markov Chain Monte Carlo (MCMC) procedures to SWAT (Abbaspour, et al., 2007). It enables sensitivity analysis, calibration, validation and uncertainty analysis of SWAT models.

3. MATERIALS AND METHODS

3.1. Description of the study area

3.1.1. Location

Lake Hawassa catchment is a closed catchment located in the central North-East of the Ethiopian Rift Valley Lakes Basin (RVLB) and covers a total area of 1352 Km^2 of which 95.2 Km^2 (around 7 % of the total area) is Lake Hawassa. The geographical co-ordinates of the catchment are 6.812^0 to 7.248^0 North and 38.280^0 to 38.726^0 East latitude and longitude respectively (see figure 3.1).

The Lake catchment contains five sub- catchments: Shashemene-Toga, Tikur-Wuha, Wedesa-Kerama, WendoKosha and Muleti. Hawassa city, named after the lake, is located at 271 km south of the capital city-Addis Ababa.

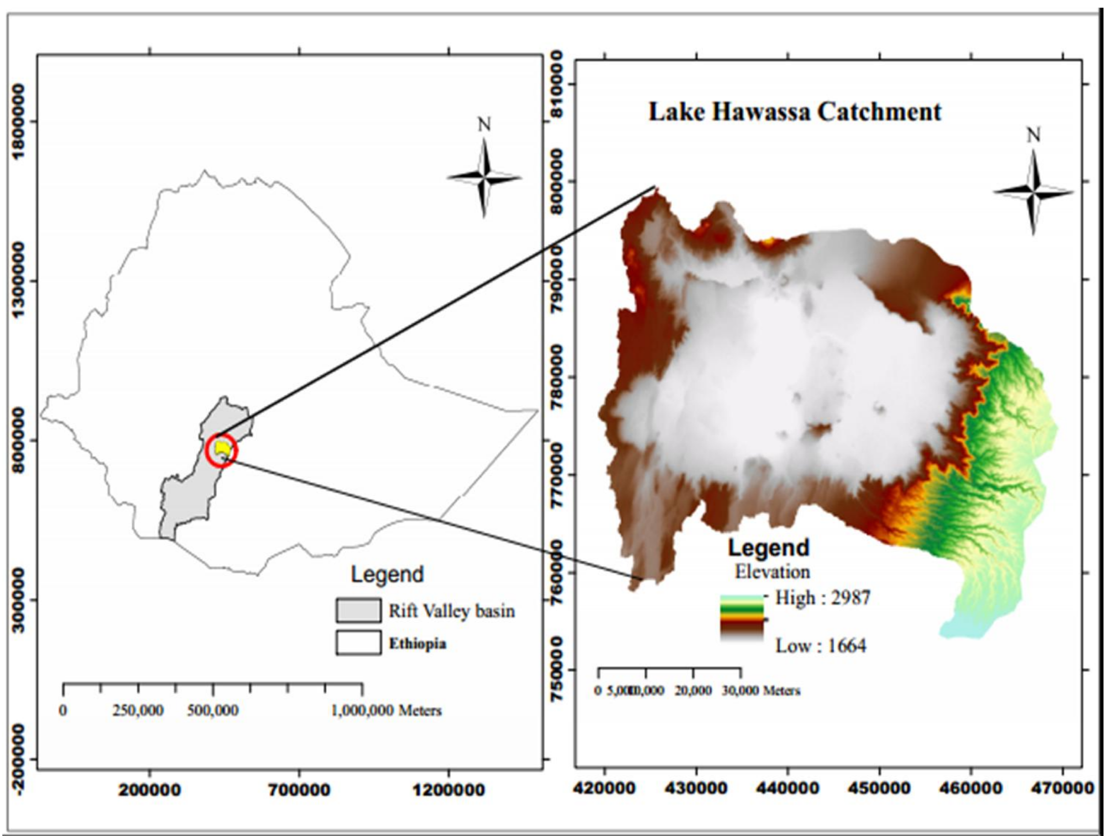

Figure 3-1: Location map of the study area

3.1.2. Climate and Agro-ecology

The climate of Ethiopia is mainly controlled by the seasonal migration of inter tropical convergence zone (ITCZ) which is conditioned by the convergence of trade winds of the northern and southern hemisphere and the associated atmospheric circulations.

The area is characterized by three main seasons. The long rainy season in the summer from June-September known locally as Kiremt and is primarily controlled by the seasonal migration of the inter-tropical convergence zone (ITCZ), which lies to the north of Ethiopia at that time. The summer rain represents 50-70% of the mean annual total. The dry period locally called bega extends between October and February when the ITCZ lies to the south of Ethiopia. Between March and May the 'small rain' season or the belg occurs when about 20-30% of the annual rainfall falls (Legesse et al., 2003). The distribution of mean monthly rainfall and mean monthly maximum and minimum temperature of different stations in the study area are given in figures 3.2 below.

The climate in the area is dry to sub humid according to the Thornthwaite's system of defining climate or moisture regions (Dessie, 1995). The mean annual rainfall on bases of the record of five rainfall stations that contribute to the watershed is estimated to be 1028mm.The lowland part of the catchment annual temperature ranges from 9^0C to 29^0C, while mean monthly temperature is 19.7^0C (Gebreegziabher, 2004)

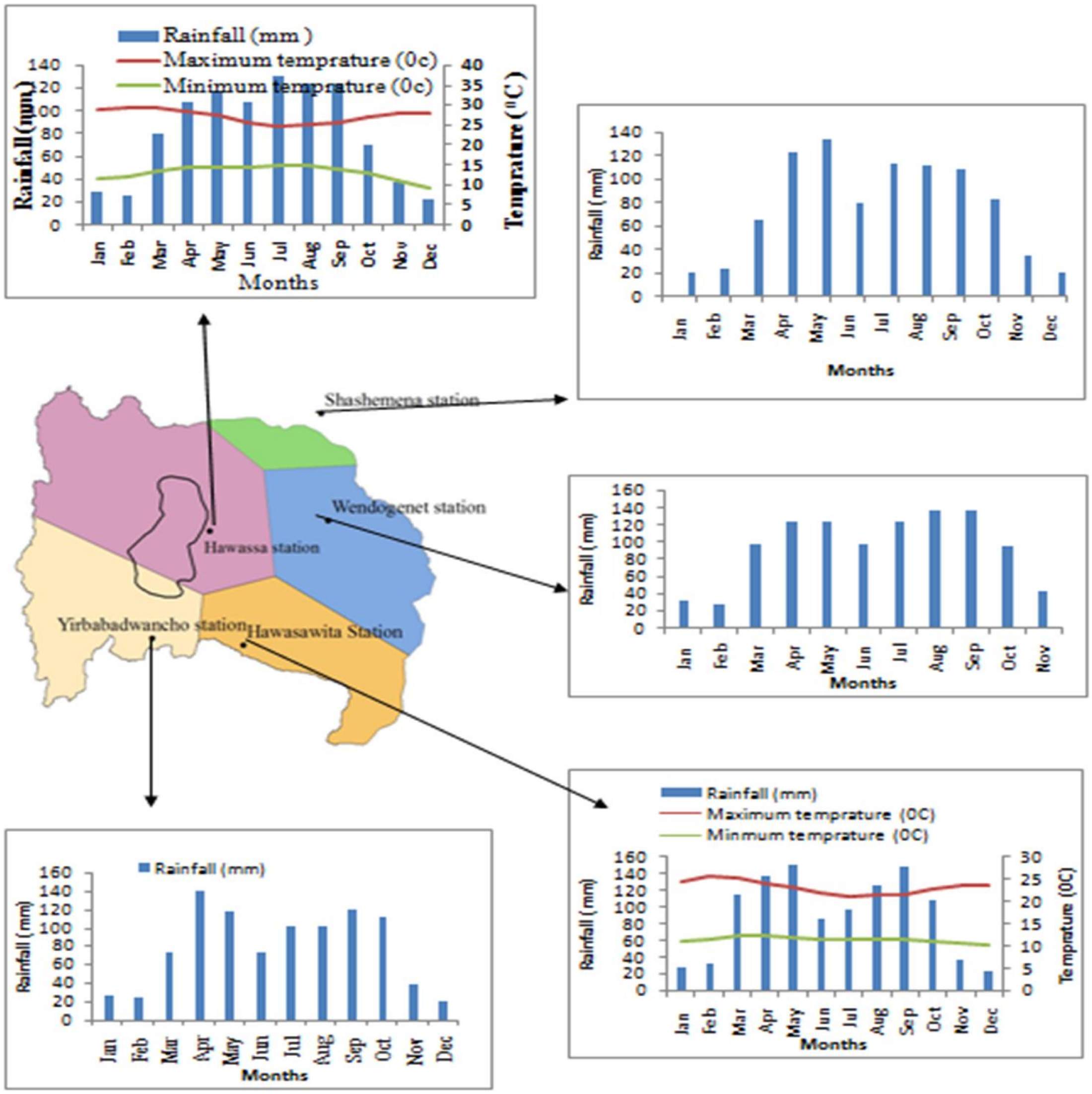

Figure 3-2: Distribution of mean monthly rainfall and maximum and minimum temperature of different stations in the catchment and catchments' Thiessen polygon.

3.1.3. Topography

The lake catchment mainly is characterized by a flat-lying topography with scattered small hills. Elevation of the area generally ranges from 1664 m.a.s.l. at to 2987 m.a.s.l. comprising escarpments, ridges, plateau, undulating to rolling and dissected plains, depressions, and swamps. Most slopes (56%) are flat to gentle (0%–8%) with a further 33% moderately sloping (8%–30%) and only 5% steep to very steep (>30%) (Dessie, 1995). Figure 3.3 demonstrate the topographical variations in the catchment.

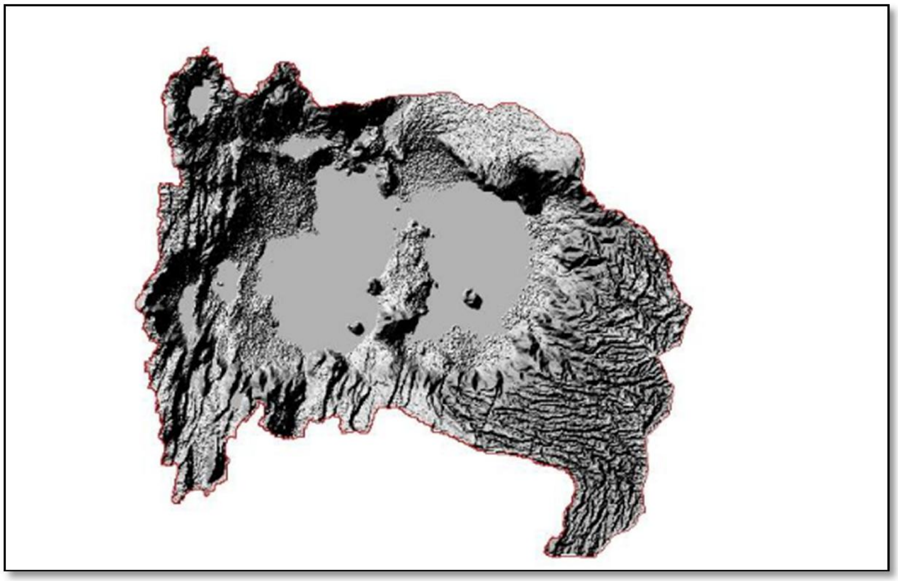

Figure 3-3: Hill shade view of the catchment landscape as processed from DEM.

[Source: Belete, (2013)]

3.1.4. Water resources

The Lake Hawassa catchment drains an area of about 1466.37 km^2, mostly from the eastern highlands, with no rivers to the west or north of the lake. Several streams (Gomesho, Wedesa, Wama) drain the hills to the east of Hawassa and flow into Cheleleka wetland, which in turn is drained through the Tikur-Wuha river into Lake Hawassa.

The steeply sloping and deforested uplands in the east are likely to produce runoff. Runoff from this eroded area carried heavy silt which is deposited in the swamp (former Lake Cheleleka) resulted in filling of the lake and reducing its water retention capacity. The surface area of Lake Cheleleka in 1972 was about 12 km^2 with estimated average depth of 5 meters and storage volume of about 60 Mm^3. But now the lake Cheleleka has lost its physical capacity by the deposition of sediment load in the past 35 years (WWDSE, 2001).

According to Belete, (2017) the lake surface area of Chelelka subsequently vanished into 5 km^2 in 1986; 3 km^2 in 1995; 1 km^2 in 2000 and left with very few square meters in 2007 and 2016 .

Tikur Wuha River is the major river in the catchment and gauged near Dato village since 1989 which provides a good point for flow measuring and monitoring in a catchment. The gauged inflow records show an annual average total flow of 113 Mm^3/year at an average flow rate of 3.53 m^3/s with an annual average specific yield of 0.10 Mm^3/km^2. The inflow has total annual sediment load of 1.7Mm^3 and an annual sediment yield of 1,600 tones / km^2/year (MoWR , 2010). Figure 3.4 below presents average annual discharge of Tikur wuha stream.

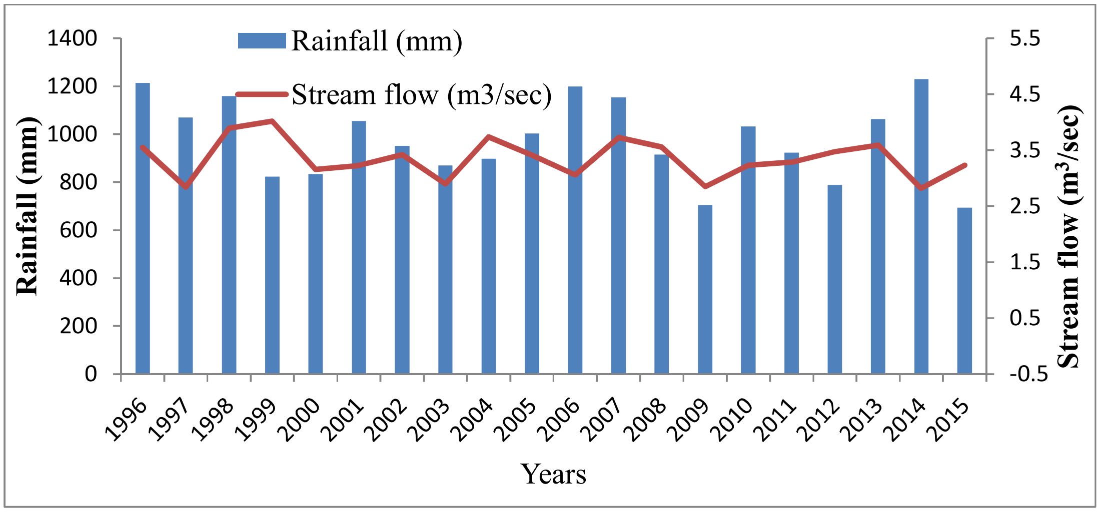

Figure 3-4: Annual discharge of Tikur wuha stream flow and annual rainfall distribution of the catchment (1996-2015)

According to Gebreegziabher (2004) Lake Hawassa is a large, shallow terminal lake with an average lake area of 87.78 Km^2 and an average depth of 13.6 m. There are seasonal variations in lake water levels, on average about 0.66 m, but range from 0.09m to 1.57m. There was a rise in relative water levels from the mid 1980s to a peak in November 1998 of 3.8 m. Since then, the lake water levels have fallen to more normal levels. The main out flows from the lake are due to subsurface flow, evaporation and abstraction for irrigation purposes.

The groundwater resource is difficult to quantify but estimated at 2.6 Mm^3/year. Groundwater quality is a serious concern, with the lowland wells especially showing high fluoride concentrations. High fluoride water cannot be used for drinking without expensive treatment (MoWR , 2010).

3.1.5. Demography

There are rural and urban population lives in Lake Hawassa catchment. According to the Central Statistical Agency (CSA) population projection of Ethiopia the total projected catchment population in the year 2015 was 1,290,824 of which 923,641 (71.3 %) are rural and 370,098 (28.7 %) are urban (CSA, 2013).

Most of the population depends on agriculture that directly or indirectly is related to the water resources of the catchment including Lake Hawassa, feeder rivers and groundwater.

The population of Hawassa town increased from 41,138 in 1987 to 301,514in 2015 (CSA, 1988 & 2013). Rural-to-urban migration and natural growth are the causes for the population growth in the town.

3.1.6. Livestock population

The total livestock population it the catchment in the year 2007 was estimated to be 516,159 cattle, 95,035 sheep, 95,035 goats, 12,763 horses, 28,912 donkeys, 486 mules, 270,936 poultry and 8,294 bee colonies (GIRD , 2008). The relatively better vegetation cover and less land degradation in the east have created conducive conditions for cattle and sheep. As a result, the population is correspondingly higher. Transferring this data into tropical livestock units (TLU) is equivalent to 449,532 TLU livestock population. The livestock composition is biased toward cattle, which accounts for 90% of the livestock. The livestock density is calculated as 335 TLU/km^2. This ranges between 286 TLU/km^2 for eastern part of the sub-basin to 410 TLU/km^2 for the west (GIRD , 2008).

3.2. Data Collection and Preparation

3.2.1. Time series data

Meteorological Data Processing: - Meteorological data are the most important data in hydrological simulation. The source of raw meteorological data in Ethiopia is the National Meteorological Service Agency (NMSA). The meteorological data obtained from this agency includes precipitation, maximum and minimum air temperature, sunshine hour, wind speed, and relative humidity in daily basis. The collected data covers a period of from1996 to 2015.

The meteorological station selection was done based on the stations length of record period, continuity of the data, concurrent period of observation and distribution of stations in and around the catchment. Generally based on the above criteria five stations which have better quality and long period daily records were selected for this study and monthly rainfall distribution of the selected stations shown in figure 3.5.

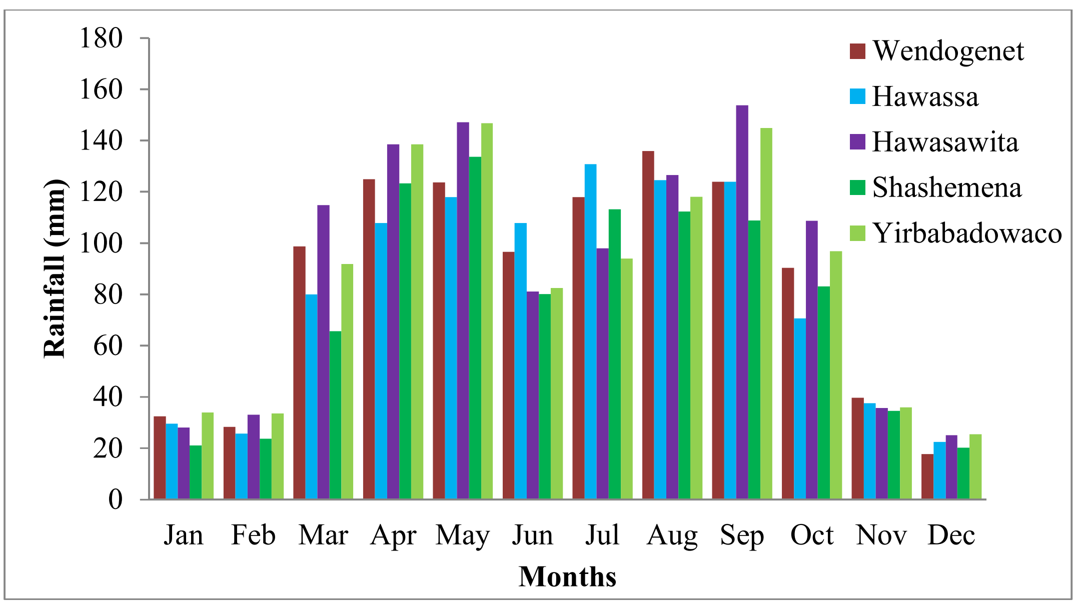

Figure 3-5: Monthly Rainfall distribution of the weather stations within and around the Lake Hawassa catchment.

The selected stations data should be stationary, consistent, and homogeneous when they are used to simulate a hydrological system. Therefore, before using the selected stations data for specific purpose, the data have to be checked and errors have to be removed using the following methods.

Filling missing rainfall data:- The first most important time series data necessary for this study is rainfall data. Sometimes the rainfall amount at certain rain gauge stations for a certain days may be missed due to damage or fault in a rain gauge during a certain period. In such cases, it may be needed to estimate the missing rainfall amount by approximating the value from nearby stations.

Different methods (Normal ratio method, inverse distance and Arithmetic mean method) are available for filling missed records of the stations data.

The normal-ratio method is recommended to fill the missing data of a gauge station if the total annual rainfall at any of the nearby gauges differs from the annual rainfall at the point of interest by more than 10% (Dingman, 2002). Thus, in this study missing records of the rainfall stations were estimated by using the normal ratio method (NRM).

The NRM can be computed using the equation 3.1 below

$$P_x = \frac{N_x}{n}\left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + \cdots \frac{P_n}{N_N}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \, eq. 3.1$$

where $p_1, p_2, \ldots, p_n$:are the monthly rainfall data of nearby stations,

$N_1, N_{2, \ldots} N_n$:the normal annual rainfall of nearby stations,

Px: the monthly estimate values of the missing station x in question

N_x : the normal annual rainfall of the missing station x and

n: is the number of stations surrounding the station x.

Checking consistency of the selected stations by double mass curve:-If the conditions relevant to the recording of a rain gauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of that station. This inconsistency would be felt from the time the significant change took place. The checking for inconsistency of a record is done by double mass curve technique (Subramanya, 1998).

Double mass curve is a graphical method for identifying and adjusting inconsistency in a station record by comparing the accumulated totals of the gauge in question with the corresponding totals for a representative group of nearby gauge. If a decided change in the regime of the curve is observed it should be corrected by using equation 3.2 below.

$$P_m = \frac{M_c}{M_a} P_x \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. Eq. 3.2$$

Where:

P_m is corrected precipitation at any time period,

P_x is original recorded precipitation at time period,

M_c is corrected slope of the double mass curve and

M_a is original slope of the double mass curve.

The checking for consistency of a record is done by double mass curve technique as shown in figure 3.6.

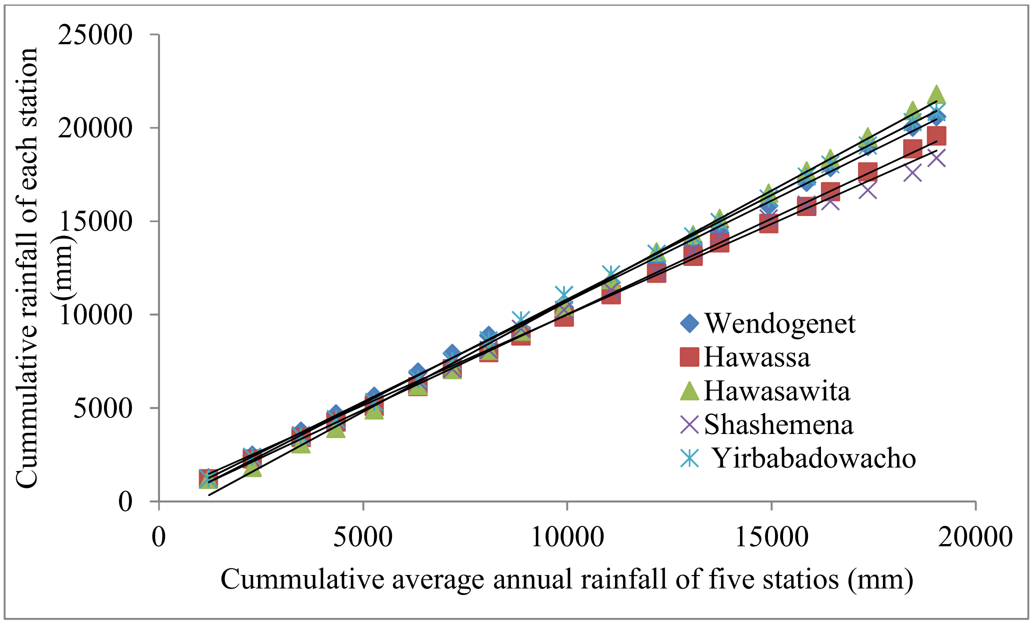

Figure 3-6: Consistency tests of rainfall data

From Figure 3-6 the double mass curve the stations used in this study have not undergone a significant change during the base line period of the study. Therefore, the stations did not need further adjustment.

Hydrological Data processing:-Stream flow data was the main data set in this study. Tikur Wuha river flow data measured near Dato village (444785 m north 784762 m east) was used for calibration and validation of the model. This data was obtained from hydrological department of the ministry of water energy and electricity, from 1996 to 2015 G.C.

The collected daily stream flow data have missed values and some records are unreliable. Therefore, it becomes necessary to supplement the missing records. In this study the multiple regression method was used to fill the missed records.

Lake level data:- The Lake Hawassa daily lake water level data also obtained from hydrological department of the ministry of water energy and electricity for the period of 1999-2014 that has been used in lake water balance analysis for determining the lake storage volume.

Evapotranspiration:- Knowledge of evaporation is a major importance in water resources assessment among others to determine the amount of water lost through the process of evaporation in the water balance computations of land, rivers, lakes and reservoirs. Evaporation is considered from two aspects: evaporation from an open water surface and evapotranspiration, which is the evaporation of intercepted water and transpiration from vegetation. The amount of water evaporated from a water surface is estimated by the following methods by using evaporimeter data, empirical evaporation equations, and analytical methods. The analytical methods provide better results, they involve parameters that are difficult to assess or expensive to obtain (subramanya, 2008).

In order to compute potential evaporation or reference evapo-transpiration, a number of methodologies are available which include Penman and its modification based type equations like Penman-Monteith, Temperature type equations like; Blanely-Criddle method and Thornthwaite method (Maidment, 1993).

According reported in FAO revised methodology, the Penman- Moteinth equation provides the best method for the evapo-transpiration and evaporation computation. Therefore mean monthly evaporation are estimated based on FAO-CROPWAT 8 program which is based on the penman monteith model. The result is given in figure 3-7.

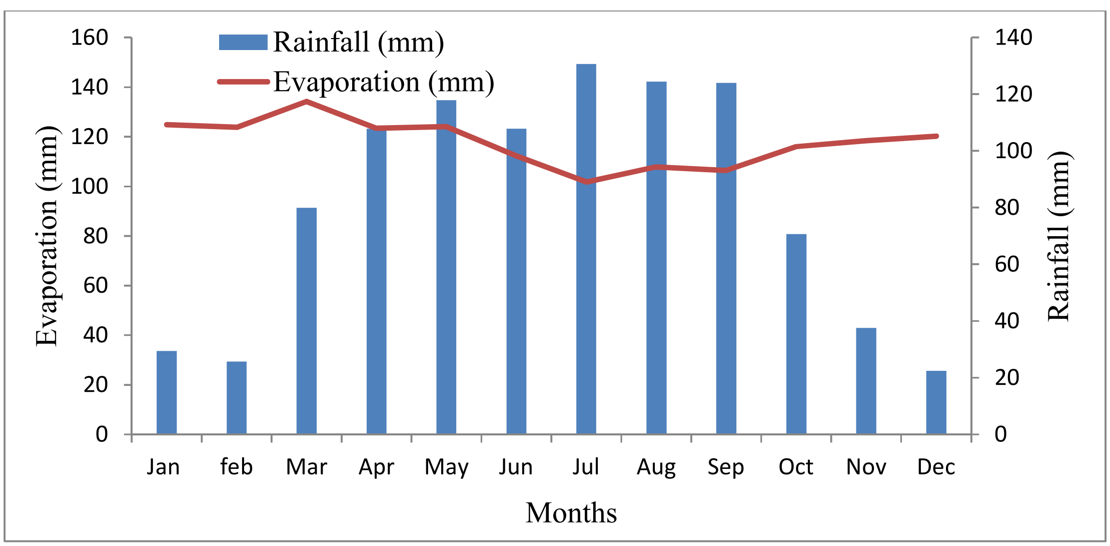

Figure 3-7: Distribution of mean monthly evaporation of the catchment

3.2.2. Spatial data

Digital elevation model (DEM) data:-The digital elevation model (DEM) is digital representation of a topographic surface and it is specifically made available in the form of raster or regular grid of spot heights. Topography is defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution.

To delineate the catchment boundary and sub- catchments, and to analyze the drainage patterns and stream networks SWAT uses the DEM. And also topographic 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. This was performed by the pre-processing module of the SWAT but requires a so called minimum threshold area.

The Lake Hawassa catchment was delineated and River networks were generated from DEM. The DEM for this study area shown in Figure 3.8 was obtained from ministry of water, irrigation and electricity and it has a resolution of 30 m x 30 m.

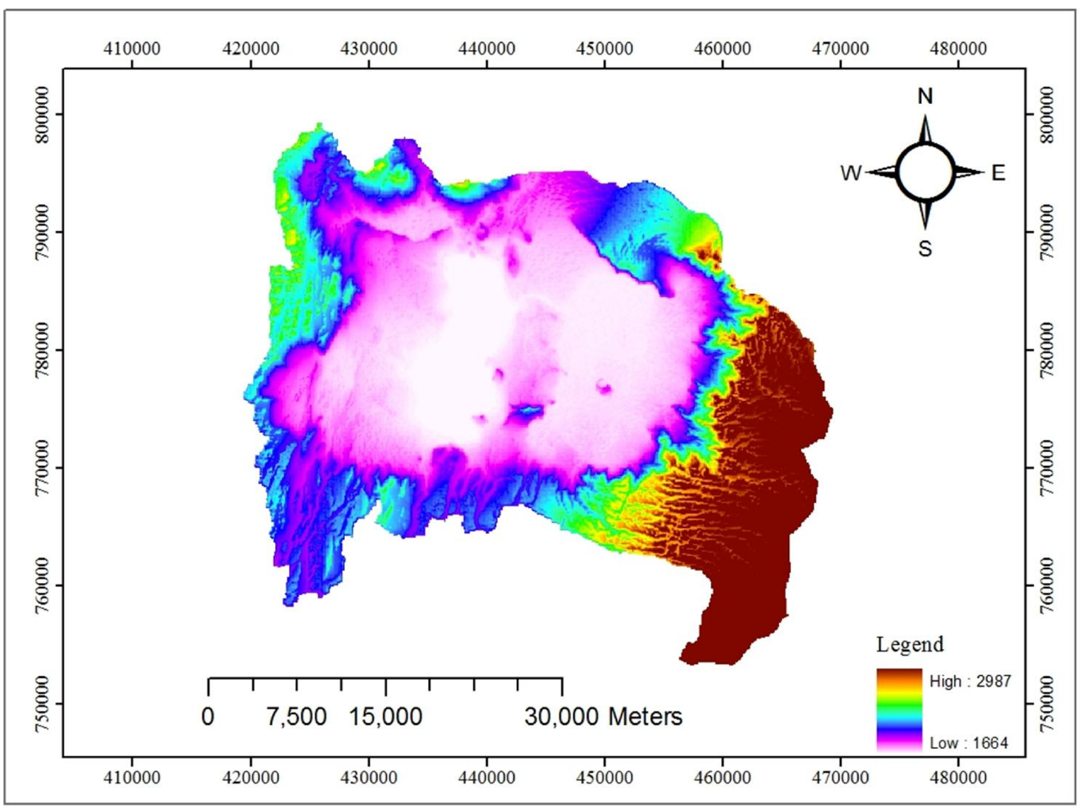

Figure 3-8: DEM of Lake Hawassa catchment

Soil data:-The soil map obtained from central rift valley lakes basin authority was used to identify the soil distribution of the catchment to be used on SWAT. According to their texture, five major and dominant soil types are identified in the catchment. According to MoWR, (2010) the most dominant soil types are, Cromic luvisols (33.7%), Eutric Fluvisols (32.7%), mollic andosols (9.8%), Eutric Leptosols (9.7%), Eutric Vertisols (3%), and the remaining area is covered by lake and swap (11.1%).

The textural and physicochemical tabular properties of the catchment soils required by the SWAT model include soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. The value of these different soil parameters (properties) for each soil type and soil layer was collected from harmonizes world soil database viewer program (FAO, 2012). Some of the data inputs and parameters were obtained by using Soil-Plant-Air-Water (SPAW) software. The soil parameter values used are listed in Appendix B. Figure 3.9 below shows the distribution of different soil type in the catchment.

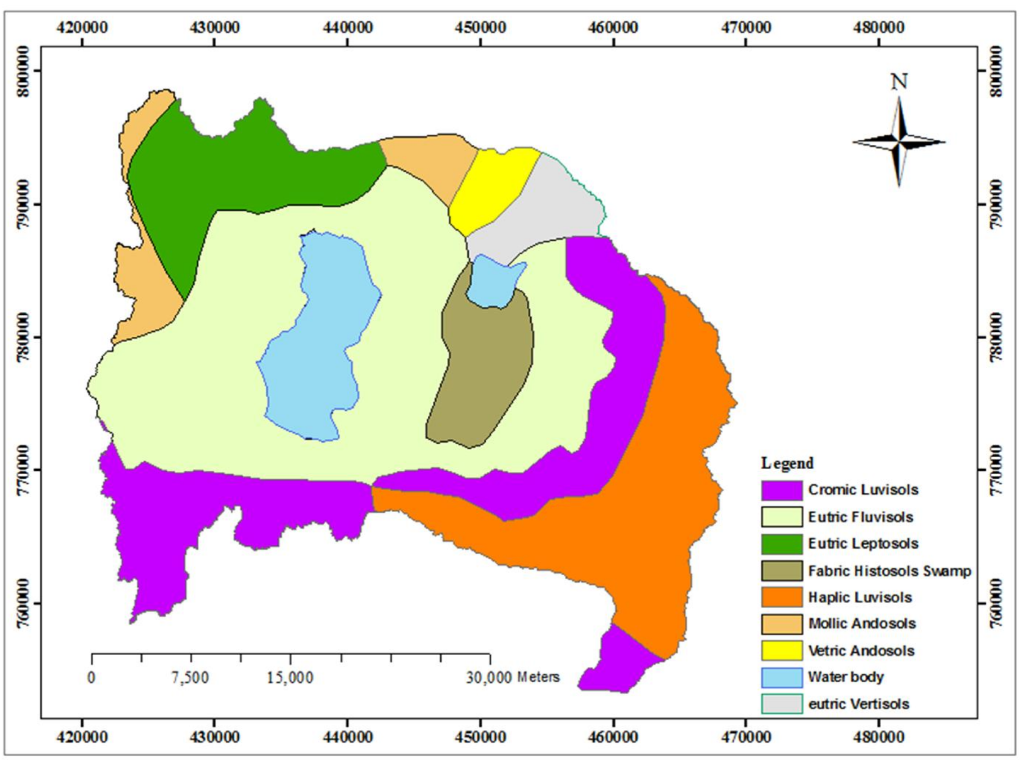

Figure 3-9: Soil map of Lake Hawassa catchment

Soil wetness index (SWI):-Catchment topography plays an important role in spatial distribution of soil properties and control on hydrological processes. It also has a major role in improving saturation excess surface runoff estimation in hilly landscapes.

Easton et al. (2008) proposed topographic wetness index (TWI) to redefine HRUs to predict Variable Saturation Areas (VSAs) for the catchments dominated by saturation-excess runoff. The method to quantify this control is soil topographic index.

Soil topographic index (Soil wetness index (SWI)) was prepared using slope, flow accumulation, soil transmissivity (Ksat) and soil depth (cm) to derive SWI map by implementing equation 3.3 below (Gessler et al., 2014) in ArcGIS raster calculation icon.

$$STI = \text{Natural}\log(\ln)\left[\frac{\text{Flowaccumulation(map)}\times\text{cellsize}\times\text{cellsize}}{\text{Tan(slopmap(radians))}\times\text{(Ksat(map))}\times\text{soildepth(map))}}\right] \ldots\ldots eq.3.3$$

The topographic index for each grid cell was computed based on upslope contributing area per unit length of contour and topographic slope of the cell. DEM was used to prepare slope (in radiance) and flow accumulation maps using ArcGIS. To convert slope in degree to slop in radian multiply slope in degree by π/180 in raster calculator or in model builder. The soil topographic index map of Lake Hawassa catchment is presented in figure 3.10 below.

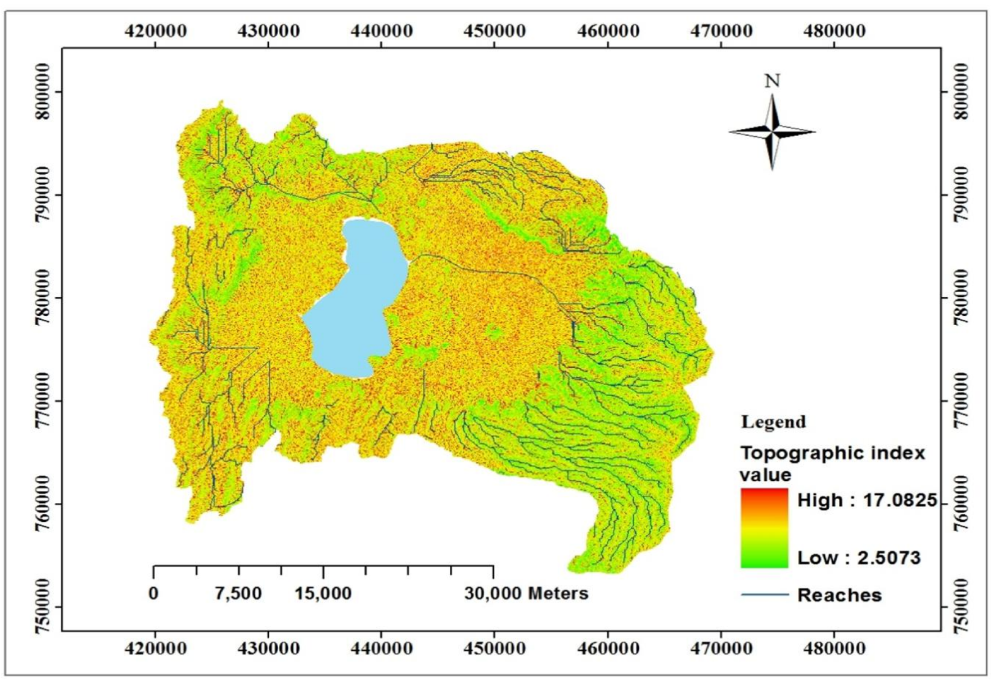

Figure 3-10: Soil topographic index map for the lake Hawassa catchment

The product of soil depth and saturated hydraulic conductivity of the soil is soil transmissivity. To generate the map of soil transmissivity (m^2/day), use the Raster calculator to multiply soil depth map (cm) by saturated hydraulic conductivity map (mm/hr) and by with the unit conversion factor of $0.0000024 = ((1/10^5) \times (1/100)) / (1/24)$. The grids include only topographical information. It makes use of an index of hydrological similarity based on topographic data.

Land use and/or land cover:-Land use is the way in which land is used by people in an area to produce what is needed by the people for use through involvement of labor, capital and available technology whereas land cover is observed physical cover on the earth's surface.

The land use land cover map of the area was prepared from the Landsat 8 satellite image with a spatial resolution of 30 m. The satellite image of the area was downloaded from USGS database website (http://earthexplorer.usgs.gov) by entering the path (168) and row (055) of the area.

LANDSAT image of 2014 was used for the preparation of land use land cover map based on supervised classification technique in EARDAS IMAGINE 2014 software using a ground truth data points collected from field observation, topographic map and Google earth.

To carry out land sat image processing the first step is stacking the reflective bands of downloaded image into single image without thermal band. Then preprocessing of the image follows to correct errors that are introduced during scanning, transmission and recoding of the data. After the above steps subset the image by area of interest (study area polygon shapefile) to make the image ready for signature editing and classification. Finally classifying the image with signature editors created with previously known land use points. The land use map of the catchment prepared based on supervised classification shown in figure 3.11 is used for this study.

Land use coverage of the catchment indicates that Agricultural land, woody vegetation and Forest (53.58 %, 13.94 % and 5.64 %) are dominant land uses. The agricultural land cover commonly consists of maize, wheat, legume, bean, vegetables, inset, fruit and coffee. The woody vegetation land dominantly covered by perennial crops consists of shade trees with coffee, banana, inset, chat and sugarcane. Built up land consists of urban area such as

Hawassa town, and other small towns such as Tikur Wuha, Wendogente, Busa, Tula. The rest portion of the catchment is covered by shrub land, wet land, grass land, bare land and lake.

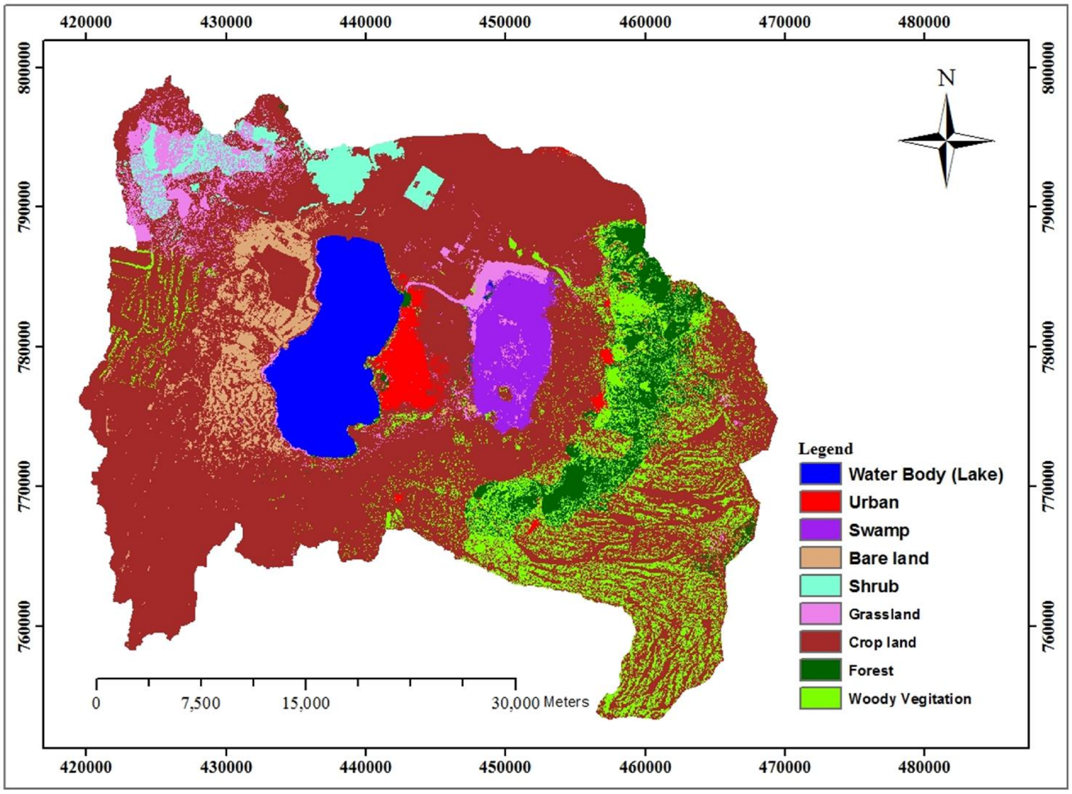

Figure 3-11: Land use map of study area

Land use land cover is one of the most important spatial input data for SWAT model that affects runoff, evapotranspiration, surface erosion and other hydrological process in a given catchment. Spatial distribution and specific land use parameters were required for modeling. SWAT has predefined land uses identified by four letter codes and it uses these codes to link land use maps to SWAT land use database in the GIS interface. Hence, while preparing the lookup table, the land use types were made compatible with the input needs by the model.

3.3. The SWAT model setup

3.3.1. SWAT –CN method

The soil and Water Assessment Tool (SWAT) is a physically-based continuous-event hydrologic model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Arnold et al., 2012; Neitsch et al., 2005)

SWAT has been successfully applied numerous times for long term continuous simulations of flow, soil erosion, and sediment and nutrient transport in watersheds of different sizes, and having different hydrologic, geologic, and climatic conditions. The model has been useful to study impacts of certain climate changes on long term water yields, and the impacts of certain management scenarios on long term sediment and nutrient loads, in addition to water yields.

The simulation of hydrological cycle by SWAT is based on the water balance provided in equation 3.4

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \dots\dots\dots\dots\dots\dots\dots\dots Eq. 3.4$$

Where:

- SW_t is the final soil water content (mm water);
- SW_o is the initial soil water content in day i(mm water);
- t is the time (days);
- R_{day} is the amount of precipitation in day i (mm water);
- Q_{surf} is the amount of surface run-off in day i (mm water);
- E_{a} is the amount of evapo-transpiration in day i (mm water);
- W_{seep} is the amount of water entering the vadose zone from the soil profile in day i (mm water); and
- Q_{gw} is the amount of return flow in day i (mm water).

Hydrologic processes simulated by SWAT include canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, and recharge by seepage from surface water bodies, ponds, and tributary channels (Arnold et. al., 2012).

Swat uses a popular CN approach to generate runoff, but a CN has its own limitations on monsoonal climates like Ethiopia. The CN approach was designed for determining runoff in temperate climate and this method was developed by curve fitting rainfall runoff data only form the united states (temperate climate). It also inaccurately assumes that similar rainfall pattern produces the same amount of runoff independent of the time of the year (White et al., 2009) and giving a unique CN for all hydrologic response units is a problematic assumption.

White, (2009) and Easton, et al. (2010) modified SWAT to more successful and efficient hydrological model to predict hydrological process in monsoonal climates like Ethiopia. This new version of SWAT, SWAT-WB (Soil and Water Assessment Tools-Water Balance) calculates runoff volumes based on saturation excess processes.

In this study the modified SWAT model SWAT-WB is used as the result of the different mechanism of runoff production in the catchment. There are also two additional reasons for selecting SWAT-WB model. First it has already been usefully applied for saturation excess hydrological simulation in Ethiopia (White et al., 2009) and second it's better performance in poorly gauged catchments.

3.3.2. SWAT–WB method

In this method, CN is replaced by soil profile water balance (WB) for simulation of each day. The runoff is generated based on saturation excess mechanism. In this process, once the soil in the area saturate to the surface, any additional rainfall that falls irrespective of intensity becomes overland flow. For daily model particularly, partly-saturated regions, the approach were shown acceptable performance (Guswa et al., 2002). SWAT-WB uses the soil moisture routines to determine the degree of saturation deficit for each day of simulation for soil profile. This saturation – deficit (in mm H_2O) is the available storage, T, and expressed in equation 3.5 (White et al., 2009).

$$T = EDC(\epsilon - \theta) \quad \ldots \ldots \ldots \; Eq. 3.5$$

Where EDC: is the effective depth of soil profile (unit less), ε is the total soil porosity (mm), and θ is the volumetric soil moisture for each day (mm). The volumetric soil moisture varies by the day and determined by SWAT's soil moisture routine while the porosity is constant value for each soil type.

The effective depth is used to represent the portion soil profile used to calculate saturation deficit and is a calibration parameter (0 to 1). EDC will control the amount of water able to infiltrate each day by including the adjustment to the available storage and also spatially varied in such a way that higher EDC value will be used for areas with low surface runoff generation and low values are assigned to areas with a high likelihood of saturation.

The adjusted available storage is then used to determine the portion of rainfall events will infiltrate and will runoff is given in equation 3.6.

$$Q = \begin{cases} 0, if\ P < T \\ P - T, if\ P \geq T \end{cases} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eq. 3.6$$

Where Q is surface runoff (mm) and P is precipitation (mm). If the rain event is larger in volume than T, the soil profile will be saturated and surface runoff will occur. However, if the rain event is less than T, the soil will not be saturated and there will not be surface runoff as a result SWAT-WB is no longer reliant upon the CN method (white et al., 2009).

3.3.3. SWAT-WB model setup

Arc- SWAT, the SWAT model embedded with the geographic information system (GIS), can integrate various spatial and environmental data including soil, land cover, climate and topographic features. It is computationally efficient, uses readily available inputs and enables users to study long term impacts. All the processes of SWAT-WB can be performed through the GIS interface Arc-SWAT by making few adjustments. Therefore in this study the Arc-GIS interface Arc-SWAT was used to create swat project. The following are the key procedures necessary for modeling using SWAT. The general methodological framework employed in this research is presented in figure 3.12.

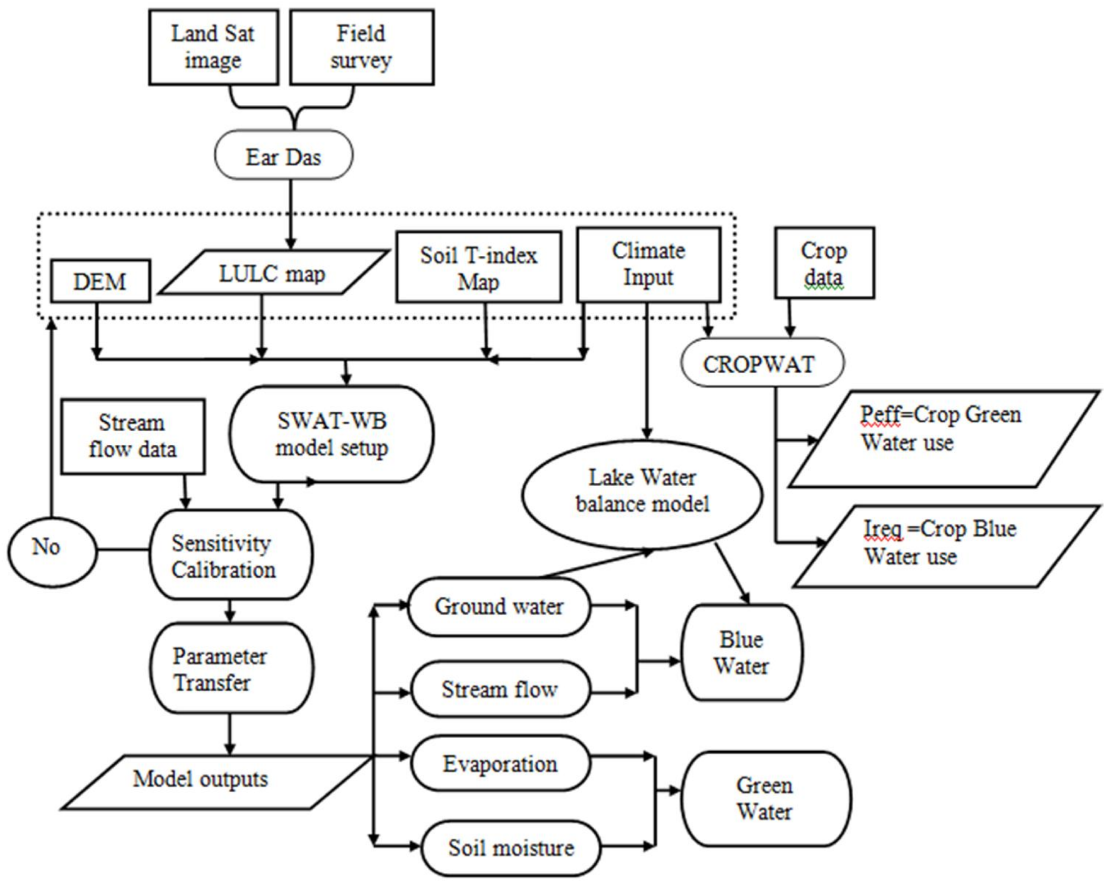

Figure 3-12: Conceptual framework of methodology

Watershed and Channel delineation:-The first step in creating SWAT model is delineation of the watershed from a DEM. The watershed delineation is separated into five sections including DEM set up, Stream definition, Outlet and inlet definition, Watershed outlet selection and Definition and calculation of sub basin parameters. In order to delineate the networks and sub basins a critical threshold value of area is required to define the minimum drainage area required to form the origin of a stream.

After the initial sub basin delineation, the generated stream network can be edited and refined by the inclusion of an outlet. Adding an outlet at the location established monitoring stations is useful for the comparison of flow concentrations between the predicted and observed data. The sub-catchment outlet, the coordinate of Dato hydrological gauging station (444785 m North 784762 m East) is manually added and selected for finalizing the watershed delineation. With this information the model automatically delineated a watershed of 649.5sqare Km and 20 sub basins were produced.

During Lake Hawassa catchment delineation (full catchment delineation) user streams and user watersheds are created to set up the program. This method is preferred because in flat areas the DEM cannot always accurately describe the topography and stream network, because gridded elevation data are often rounded to the nearest meter (Maune, 2011). The detailed method of creating user streams and user watershed described in SWAT user manual and examples are in SWAT database Exinputs.

HRU definition:- In SWAT CN hydrologic response units (HRU) are lumped land areas within the sub basin that comprised of unique land cover, soil and management combinations where as in SWAT-WB it was based on land use land cover, soil witness index (topographic wetness index derived from DEM and soil transmissivity), and slop class again from DEM. Integration of topographic wetness index derived from DEM with SWAT model helps in estimating spatially distributed surface runoff generation in the catchment(Kumar et al., 2016).

HRUs enable the model to reflect differences in evapotranspiration and other hydrologic conditions for different land covers and soils. The runoff is estimated separately for each HRU and routed to obtain the total runoff for the catchment. This increases the accuracy in flow prediction and provides a much better physical description of the water balance. The land use and the topographic wetness index in a projected file format were loaded into the SWAT interface to determine the area and hydrologic parameters of each land- soil category simulated within each sub- catchment.

The land cover classes were defined using the look up table. A look- up table that identifies the 4- letter SWAT code for the different categories of land cover land use was prepared so as to relate the grid values to SWAT land cover land use classes. After the land use SWAT code is assigned to all map categories, calculation of the area covered by each land use and reclassification were done.

As for the land use, the soil topographic index map layer in the map was linked to the user soil database information by loading the soil look- up table and reclassification applied. The DEM data used during the catchment delineation was also used for slope classification. After the reclassification overlay operation was performed.

The second step in the HRU analysis was the HRU definition. The HRU distribution in this study was determined by assigning multiple HRU to each sub- catchment. In multiple

HRU definition, a threshold level was used to eliminate minor land uses, soils or slope classes in each sub basin. Land uses, or soils which cover less than the threshold level are eliminated. Due attention was given to the threshold value of HRU because Setegn et al. (2010) reported that SWAT model was more sensitive to HRU definition thresholds. In the SWAT user manual it is suggested that it is better to use a larger number of sub- basins than larger number of HRUs in a sub basin; maximum of 10 HRUs in a sub basin is recommended. Recommended thresholds of 20% for land cover also for soil and 10% for the slope area were applied to limit the number of HRUs in each sub watershed.

Hence, taking the recommendations in to consideration, 15% threshold levels for the land use and soil, and 10% for slope were applied in this study, so as to encompass most of spatial details. After the threshold definition process, the area of the remaining land use, or soil was reapportioned so that 99.8% of the land area in the catchment is modeled. The threshold levels set is a function of the project goal and amount of detail required.

Weather data definition:-Meteorological records (precipitation, minimum and maximum temperature, relative humidity, solar radiation and wind speed) and location of meteorological stations were prepared based on SWAT table format and integrated with the model using weather data input wizards.

Solar radiation, relative humidity, and wind speed data were available only for principal Hawassa station. These data‘s for the rest of the stations were generated by SWAT weather generator. WXGEN weather generator was prepared with all the necessary statistical information from the meteorological records of the Hawassa station with the use of different tools.

Simulation:-SWAT simulation run was carried out for the period of starting from 1996 to 2015. The first three years taken for warm up period. The warm up period is important to make sure that there are no effects from the initial conditions in the model. After adding of soil bee files and SWAT-WB.exe applications into textinout folder in the project directory the model setup was ready to run SWAT-WB.

After the model set up has been completed the next step is run the SWAT-WB exe application and the result from the simulation cannot be directly used for further analysis. Instead, the application of the model for the intended purpose was evaluated through sensitivity analysis, model calibration and model validation (White & Chaubey, 2005).

3.4. Model parameterization

When a simulation is taken place there is discrepancy between measured data and simulated results. So, to minimize this discrepancy, it is necessary to determine the parameters which are affecting the results and the extent of variation. Hence, to check this, it is important to know the type of parameters, their behavior and feasible range. Table 3.1 provides a description of 26 most common parameters included in SWAT model parameterization. The selection and description of these parameters were based on reviewing different previous researches and documentation from the swat manuals (e.g., neitsch et al., 2005; white and chaubey, 2005; setegn et al., 2010; arnold et al., 1998 and 2012)

ALPHA_BF (Base-flow alpha factor) a parameter that expresses the recession or the rate at which the groundwater is returned to the flow. GW_DELAY (Groundwater delay in day), which is defined as the required time for water leaving the bottom of the root zone to reach the shallow aquifer where it can contribute to lateral groundwater flow. GW_REVAP (Groundwater "revap" coefficient) which is a dimensionless coefficient controlling the rate of water movement between the root zone and the shallow aquifer. GWQMN (threshold depth of water in the shallow aquifer required for return flow to occur in mm). The REVAPMN defines the threshold depth of water in the shallow aquifer for return flow to the root zone to occur, and is particularly important in areas with high water tables or those with deep-rooted crops.

SOL_K relates soil water flow rate to the hydraulic gradient and is a measure of the ease of water movement through the soil. SOL_AWC is the available water capacity of the soil layer, which is available for the plants.

ESCO, which is the soil evaporation compensation factor which directly influences the evapotranspiration losses from the watershed, a parameter depends on soil characteristics and controls the soil evaporation. The ESCO factor varies between 0.01 and 1. A lower value allows the model to extract more of the evaporation demand from lower levels.

EPCO, which is the plant uptake compensation factor and expresses the amount of water needed to meet the plant uptake demand.

Table 3-1: Most common parameters used in SWAT-WB model and their range

No	Parameter	Definition	Lower Bound	Upper Bound	Range
1	Alpha_Bf	BAseflow alpha factor [days]	0	1	0 - 1
2	Gw_Delay	Groundwater delay [days]	-10	10	0 - 500
3	Gw_Revap	Groundwater "revap" coefficient	-0.036	0.036	0 .02 - 0.2
4	Gwqmn	Threshold depth of water in the shallow aquifer required for return flow to occur [mm]	-1000	1000	0 -5000
5	Revapmn	Threshold depth of water in the shallow aquifer for "revap" to occur [mm]	-100	100	0 - 500
6	Ch_K2	Effective hydraulic conductivity [mm/hr]	0	150	0 - 500
7	Ch_N2	Manning's n value for main channel	0	1	0 - 0.3
8	Canmx	Maximum canopy storage [mm]	0	10	0 - 10
9	Epco	plant water uptake compensation factor	0	1	0 - 1
10	Esco	soil evaporation compensation factor	0	1	0 - 1
11	Sol_Alb	Soil Albedo	-25	25	0 – 0.3
12	Sol_Awc	soil available water capacity	-25	25	0 - 1
13	Sol_K	hydraulic conductivity of saturated soil	-25	25	0 - 2000
14	Sol_Z	Depth from soil surface to bottom of layer (mm)	-25	25	0 - 3500
15	Cn2	curve number	-25	25	35 -98
16	Biomix	Biological mixing efficiency	0	1	0 - 1
17	Surlag	runoff delay coefficient	0	10	0 - 10
18	Sftmp	Snowfall temperature	0	5	-5–5
19	Slope	Average slope steepness [m/m]	-25	25	0 - 999
20	Slsubbsn	Average slope length [m]	-25	25	10 - 150
21	Smfmn	Melt factor for snow on December 21 [mm H2O/ºC-day]	0	10	0–5
22	Smfmx	Melt factor for snow on June 21 [mm H2O/ºC-day]	0	10	5–10
23	Smtmp	Snow melt base temperature [ºC]	-25	25	-5–5
24	Timp	Snow pack temperature lag factor	0	1	0–1
25	Tlaps	Temperature lapse rate [°C/km]	0	50	0 - 50
26	Blai	Maximum leaf area index(m^2/m^2)	0	1	0.5 - 10

Channel hydraulic conductivity (CH_K2) is used to estimate the peak runoff rate. BLAI represent the maximum potential leaf area index of trees. BLAI is one of the six parameters used to determine leaf area development of plants during the growing season.

SURLAG which controls the fraction of the total water that is allowed to enter the stream on any specific day.

Snow parameters (eg, Smfmn, Smfmx , Smtmp) are not included in the sensitivity analysis of this study, since the study site belongs to a semi-arid climate and the flow is not affected by the snow melt process.

Sensitivity analysis:- It is especially important in SWAT model which is a comprehensive conceptual model that relies heavily on several parameters varying widely in spatial and temporal scales while transforming input into output. The sensitivity analysis setup was done using a built-in SWAT sensitivity analysis tool. The inputs were the observed monthly flow data and parameter in relation to flow with the absolute lower and upper bound and default type of change to be applied method of application was used. It was checked by the Dato gauging station flow data of Tikur Wuhu River.

After running sensitivity analysis, the sensitive parameters were categorized into four classes based on their mean relative sensitivity from very high to small according to the table 3.2.

Table 3-2: Sensitivity classes

Class	Index(I)	Sensitivity
I	$0.00 \leq \lvert I \rvert < 0.05$	Small to negligible
II	$0.05 \leq \lvert I \rvert < 0.20$	Medium
III	$0.20 \leq \lvert I \rvert < 1.00$	High
IV	$\lvert I \rvert \geq 1.00$	Very high

Source: Lenhart et al.(2002)

Model calibration:- Nearly all hydrological models need some sort of calibrations to reach acceptable performance. SWAT model calibration is a means of adjusting or fine-tuning model parameters to match the simulated results with the observed data as much as possible there by reducing the prediction uncertainty.

After parameter sensitivity analysis was undertaken to identify key flow parameters, the SWAT models were calibrated for stream flow of the sub catchment recorded at its outlet. It is performed by carefully selecting values for model input parameters by comparing model prediction (output) for a given set of assumed conditions with observed data. The calibration was done by changing the parameters sequentially for obtaining optimum agreement between observed and simulated stream flow.

In this study, flow calibration was performed using observed data for a period of 11 years from 1999-2009 since the first three years (1996 and 1998) were set as a warm up period. Calibration of stream flow carried out at outlet of sub basin no 1 (near Tikur Wuha). This site was selected due to the availability of measured flow data. The stream flow calibration was on monthly average time steps.

Model Validation:-Model Validation is the process of representing that a given site specific model is capable of making accurate predictions. This was done by applying the calibrated model using a different data set out of the range of calibration without changing the parameter values. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits (Reuben, 2007).

Model validation is similar to model calibration in that the predicted and measured values are compared to determine the model fit to the observed data. Stream flow data of six years from 2010 to 2015 were used for validation.

3.5. Model performance evaluation

In order to evaluate the model's simulation performance relative to the observed data, the following two performance measures were used: coefficient of determination (R^2) and Nash Sutcliffe simulation efficiency (E_{NS}) as used by various researchers (e.g. Easton et al., 2010; Zeng et al., 2012; Tekle and Abebe, 2016; Halefom et al., 2018).

The regression coefficient (R^2) is the square of the Pearson product–moment correlation coefficient and describes the proportion of the total variance in the observed data that can be explained by the model. The closer the value of R^2 to 1, the higher is the agreement between the simulated and the measured flows and calculated as equation 3.7.

$$R^2 = \frac{\left[\sum_i^n (Q_{o,i} - \overline{Q}_o)(Q_{s,i} - \overline{Q}_s)\right]^2}{\sum_i^n (Q_{o,i} - \overline{Q}_o)^2 \times \sum_i^n (Q_{s,i} - \overline{Q}_s)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 3.7$$

Where: R^2 coefficient of determination, Q is a discharge, and o and s stand for observed and simulated, *i* is the i^{th} observed or simulated period.

Nash and Sutcliffe simulation efficiency (ENS) indicates the degree of fitness of observed and simulated data and given by the equation 3.8.

$$E_{NS} = 1 - \frac{\sum_i^n (Q_{oi} - Q_s)^2}{\sum_i^n (Q_{o,i} - \bar{Q}_o)^2} \ldots \text{eq.3.8}$$

The value of ENS ranges from 1.0 to negative infinity. ENS value of zero means that the model predictions are just as accurate as using the measured data average to predict the measured data. ENS values less than 0 indicate the measured data average is a better predictor of the measured data than the model predictions while a value greater than 0.0 indicates the model is a better predictor of the measured data than the measured data average.

3.6. Estimating water balance components of Tikur wuha river catchment

Hydrological cycle is used to express the general circulation of water in the various forms from oceans to the atmosphere, to the ground from atmosphere, to the oceans again. Hydrological models partition rainfall into various hydrological components such as surface runoff, evapotranspiration, percolation, lateral flow and base flow based on the principle of conservation of mass. In this study the, the Tikur Wuha river catchment water balance components such as precipitation, evapotranspiration, total runoff, surface runoff, groundwater flow and the soil water content were estimated using SWAT-WB using the method discussed in this chapter.

3.7. Prediction in the ungauged sub basins

Nearly half of Lake Hawassa catchment is ungauged. It is difficult to model ungauged catchments because hydrological models need flow data to calibrate the simulation process. To overcome this challenge several methods have been developed but the popular methodology was transferring of the calibrated model parameters of gauged catchment to ungauged catchment based on similarity of catchment characteristics such as topography, slop, land cover, soil type, and climate.

Parameters transferred based on physical catchment characteristic similarity is referred to as regionalization and the adopted method in this study. Several definitions of regionalization are used in the literature, but a generic definition as stated in

Bloschl and Sivapalan (1995) is used most often. Regionalization is the process of transferring information from comparable catchments to the catchment of interest.

After thorough calibration and validation of the SWAT model for the gauged Tikur Wuha River sub catchment, the final calibrated parameters are used to predict runoff and water balance component of the ungauged part of the Lake Hawassa catchment, which have similar hydro meteorological conditions based on HRU similarity. Transferring calibrated parameters to ungauge from gauged catchment having the same HRUs as ungauged catchments. The HRUs are the basic computational units in which the overall hydrologic balance is simulated, including precipitation partitioning, surface runoff generation, evapotranspiration (ET), and soil water and groundwater movement.

The use of calibrated parameter transfer based on HRU similarity is a common hydrological modeling approach to study ungauged catchment. For instance, Tegegne et al., (2013) transferred calibrated and validated SWAT model parameters from the gauged upper reaches of major catchments of Gilgel Abay, Gumera, Rib and Megech to un-gauged catchments to estimate the ungauged flow contribution based on similarity of the hydrologic response unit (HRUs).

3.8. Lake water balance model

In order to quantify the amount of blue water stored in the lake, water balance computation is made using excel spreadsheet model based on conservation of mass by measuring and estimating the components of inflows and outflows from closed lake using the equation 3.9 below (UNSECO, 1974).

$$\pm\frac{\Delta s}{\Delta t} = p - E_v + Q_{in} - Q_{out} + G_{in} - G_{out} + Abs \dots\dots\dots\dots\dots\dots\dots\dots \text{Eq: 3.9}$$

Where

- p = Direct precipitation on the lake (m3)
- E_v = Evaporation from the lake
- Q_{in} = Surface runoff from the catchment
- Q_{out}= Runoff outflow from the lake
- G_{in} = Groundwater inflow to the lake
- G_{out} = Groundwater outflow from the lake
- Abs= Abstraction from the lake

To model the above multi step continuity equation needs to estimate the various water balance components of the lake. Thus, the model is formulated through a quantitative assessment of the inflow volumes (precipitation on Lake surface, ground water inflow to the lake and runoff – from gauged and ungauged catchments), outflow volumes (evaporation, abstraction and ground water outflow from the lake).

Precipitation on the lake surface determined from time serious rainfall data of Hawassa meteorological station since this station is near to the lake. Lake Hawassa receives perennial flow from Tikur Wuha River, measured discharge data of this river is used in the part of stream flow input from gauged catchment in water balance computation. The volume of runoff enters into the lake from the ungauged catchment computed by using runoff coefficient method (total runoff/total rainfall). To execute runoff coefficient method determination of areal rainfall of the gauged and ungaged part of the catchment is necessary. Areal rainfall of gauged and ungaged part of the catchment were determined from time series rainfall records of meteorological station in and around the catchment weighted by Theissen polygon method. The monthly lake evaporation estimation was carried out using Penman-Monteith Method. The Penman-Monteith model uses five climate variables (minimum and maximum temperature, relative humidity, wind speed, and sun-shine hours) to compute the potential evapotranspiration (ETo) which is equivalent to evaporation from the surface of open water. In this study, the monthly values of ETo were computed from monthly values of input parameters using CROPWAT 8.0 software.

Ground water inflow is estimated from SWAT-WB model results of the catchment that is the catchments ground water contribution to surface flow monthly output. With other components known, ground water outflow then estimated as residual term in the lake water balance equation.

Water abstraction from the lake for irrigation, construction and Hawassa town greenery were considered as negligible.

To simulate the water level, volume, and surface area the elevation-area-volume relationship equations for Lake Hawassa derived by Gebreegziabher (2004) shown in equations 3.10 and 3.11 below were employed in this study.

$$\text{Lake surface area (m}^2) = (4 \times 10^6 \times \text{d}) + 9 \times 10^6 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq{:}\ 3.10$$

$$\text{Lake volume (m}^3) = (2 \times 10^6 \times \text{d}^2) + (1 \times 10^7 \times \text{d}) - 5.95 \times 10^7 \ldots\ldots.\ldots\ldots. Eq{:}\ 3.11$$

Where d is the actual depth of the lake in meter

Formulation of the spreadsheet model

1. As this study starts calculating water balance from January 1999, the end of December 1998 lake volume, calculated based on the collected lake level data and the lakes' depth area volume relationship equations are directly used as initial state.
2. Updating initial state volume with each current month quantified volume of lake water balance components
3. Estimating the ground water output as a fraction of volume at the end of current month before ground water output.
4. Set starting volume of the next month as the difference between current month volume of lake after quantified water balance component and estimated ground water output
5. Repeat step 2, 3, and 4 until the end of study period
6. Iterate the constant K until a reasonable agreement is obtained between observed volume of lake and calculated volume of the lake and the procedure of calculation in excel sheet is presented in table 3.3 below.

Table 3-3: Lake Water balance calculation procedure in excel spreadsheet application

			K	0.0045							
Column number											
1	2	3	4	5	6	7	8	9	10	11	12
Month	Rainfall on the lake	Runoff from Gauged+Ungauged	Evaporation from lake	Ground water inflow		Initial Volume	State after Rainfall	State after runoff	State after Evaport	State after ground water inflow	ground water Outflow
Dec-98						X					
Jan-99						X	column 7+2	column 8+3	column 9-4	column 10+5	K* column 11
						11-12	Repeat the above procedures				

3.9. Quantification of Blue and Green water resources

Detailed assessments of the different components of freshwater availability are essential for locating significant regions, and thus, the basis for rational decision-making in water resources planning and management.

By applying a semidistributed hydrological model SWAT-WB (Soil and Water Assessment Tool water balnce), the freshwater components blue water flow (i.e., water yield plus deep aquifer recharge), green water flow (i.e., actual and potential evapotranspiration), and green water storage (i.e., soil moisture) were estimated at a cachment level with annual, seasonal and monthly time-steps.

The general water balance equation in the SWAT model may be expressed by equation equation 3.12 below, where each of the components can be associated with blue/green water fluxes or storage. For long-term mass balance, if we expect no trend in storage, then flows and losses become equal to rainfall (van Griensven et al., 2012).

$$Rainfall = Evapotranspiration + Water\ Yield + \Delta\ (Soil\ Storage) + \Delta\ (Grou\ ndwater Storage) + Losses \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 3.12$$

Blue water is represented by Water Yield (SWAT output WYLD), which is the total amount of water leaving the HRU and entering main channel, and by Groundwater Storage (difference between the total amount of water recharge to shallow and deep aquifers (SWAT output GW_RCHG) and the amount of shallow aquifer water that contributes to the main channel (SWAT output GW_Q) during the time step. Green Water is represented by the Actual Evapotranspiration (SWAT output ET), and by the Soil Water Content (SWAT output SW) as also suggested by (Schuol et al., 2008).

The model explicitly quantify hydrological components of water resources, e.g. surface runoff and deep aquifer recharge (blue water flow), soil water (green water storage) and actual evapotranspiration (green water flow).

3.10. Consumptive use of Green and Blue water

After knowing the available Blue and green water resources within the catchment, determining the consumptive blue and green water use of water demanding sectors is important to effectively manage water resource in the catchment.

The catchment characterized by fast increasing population, urbanization and industrialization in the past twenty years. With the increasing population including urbanization, economic growth, industrial production, agricultural and livestock production, demand for water has increased rapidly over those years (GWP, 2000).

Water demand is defined as the volume of water requested by users to satisfy their needs, is often considered equal to water consumption without any return flow back to the source. Consumption is the actual volume of water consumed, whereas demand is how much water people would use if they had the opportunity (Anonymous, 2003).

Increase in water demand reduces water availability during dry seasons because water resource in a catchment varies between years and within years. Unless properly managed, increasing demand of the scarce water resources by different sectors will strongly affect all users and the environment (Hellström et al., 2000).

Environmental, urban, industrial, rural domestic and agricultural sectors are potential water use sectors identified in the catchment. The detailed method of determining consumption amount of each sector was discussed below.

3.10.1. Agricultural water consumption

Agriculture is the main economic activity in the lake Hawassa catchment. Investigating the true agricultural water consumption at a catchment scale is a difficult process that requires detailed, often hard to acquire parameters. On irrigated areas, part of the water used by crops is blue by origin while another part is green by origin. At present, agriculture in the catchment is primarily rain-fed and relies almost exclusively on green-water resources (soil moisture regenerated by precipitation).

Since most farming is based on rain fed agriculture, but there is small scale irrigation mainly around the southern and western shores of Lake Hawassa and around the fringes of the Cheleleka wetlands.

Lake Hawassa sub-basin is characterized by diversified farming systems. Large number of crops with different combinations and intensity are growing in two cropping seasons. In addition to the perennial crops, farmers cultivate maize, wheat, teff, barley, haricot bean, pepper and potato during the meher season, while during the Belg cropping season they grow Maize, Teff, Haricot bean and Potato. Those farmers with access to irrigation water (either from lake or rivers) cultivate vegetables and fruit tree crops. Perennial crops like

Coffee, chat, Enset, Sugarcane, Banana, Mango and vocado are grown as part of the crop production system around homesteads and on irrigated lands.

The volume of blue water required by agricultural systems differs, depending on crops planted, agricultural management, and water lost through evaporation from the water source to the field (Johansson et al., 2016). The green and blue water concept can help estimate site-specific water use of agriculture, and refine our understanding of human impacts on freshwater resources

Crop production requires large amounts of green and blue water. Consumptive crop water use of green water and blue water has increased with the extension of agricultural land, and irrigated areas in particular (Siebert, 2007). Consumptive crop blue water use is as the amount of evapotranspiration on cropland stemming from irrigation. Consumptive crop green water use is evapotranspiration stemming from precipitation on crop-land. Total consumptive crop water use is the sum of consumptive blue crop water use and consumptive green water use and represents total actual crop evapotranspiration. Green water represents rainwater used to support crop growth through evapotranspiration (ET); blue water represents surface water and groundwater use by crop through ET. Consumptive green water for crop is computed from effective rainfall, while consumptive blue water is estimated from the differential of ET and effective rainfall.

Using the CROPWAT model (FAO, 1998), the crop evapotranspiration (ETc) and the available effective rainfall are calculated for the given set of data on ETo, monthly rainfall, Kc and the crop calendar. The CROPWAT model needs climate, crop and soil parameters to model evapotranspiration and crop irrigation requirements. Climate data include temperature, precipitation, humidity, sunshine, radiation and wind speed. Crop parameters such as crop coefficients, rooting depths, lengths of each crop development stage, the planting and harvest dates are obtained from literatures and sidama zone agri development office.

The reference crop evapotranspiration (ETo) derived using the Penman–Monteith equation, given by:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq: 3.13}$$

Where

ETo reference evapotranspiration [mm day-1],

Rn net radiation at the crop surface [MJ m-2day-1],

G soil heat flux density [MJ m-2day-1],

T mean daily air temperature at 2 m height [°C],

U_2 wind speed at 2 m height [m s-1],

e_s saturation vapour pressure [kPa],

e_a actual vapour pressure [kPa],

e_s-e_a saturation vapour pressure deficit [kPa],

Δ slope vapour pressure curve [kPa °C-1],

γ psychrometric constant [kPa °C-1].

The Food and Agriculture Organization (FAO) of the United Nations recommend the use the Penman-Monteith equation as the sole method for the estimation of reference crop evapotranspiration.

The Food and Agriculture Organization (FAO) of the United Nations recommend the use of the Penman-Monteith equation as the sole method for the estimation of reference crop evapotranspiration.

The CROPWAT model (FAO, 2010; Allen et al., 1998) is used to estimate effective rainfall and irrigation requirement of crops. The monthly crop-specific evapotranspration value is summed to annual evapotranspration, together with the effective rain and crop area, to obtain the green and blue water use.

The effective rainfall was obtained by applying the definition and method proposed by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) in CROPWAT model 8.0 which accounts only for precipitation available for crop consumptive use. It is assumed that there is no further runoff or deep percolation of the precipitation after an effective rainfall.

The green water use in irrigated areas was calculated by multiplying the green water use of major crops (m^3/ha) by the total area. Blue water use is calculated by multiplying the irrigation requirement of major crops with the total irrigated area. Total water demand for irrigation will be thus estimated by multiplying the total area under irrigation with the average water requirement for the main crops.

3.10.2. Livestock water consumption

No livestock census has ever taken place in Ethiopia. The basis for livestock population estimates are those data prepared by the Central Statistical Authority and Ethiopian livestock research institute (ELRI). The livestock resource of the catchment is primarily indigenous comprised of cattle, sheep, goats, horses, donkeys, mules and poultry with a total some of 458,541.4 tropical livestock units (TLU), the majority of which are cattle. For estimation of livestock water demand, FAO livestock water demands standard in semi-arid regions have been used for the different types of the livestock available in the study area. In this study livestock water use was computed as the sum of product of the number of animals in each livestock class times a per capita usage for each livestock class unit.

3.10.3. Urban Water consumption

In this study the urban water consumption includes water used for domestic house hold use, commercial water use for hotels, restaurants, shops and offices, and Institutional water use for Universities, Hospitals, Collages and Schools. And also includes water use of small industries within the urban area they get their water from public water supply. The urban water consumption was computed indirectly by calculation the amount of water delivered by Towns Water Supply and Sewerage Service offices and ground water abstraction of hotels, pensions and car washing plants having their own well.

3.10.4. Rural domestic water consumption

The domestic water consumption is the volume of water for domestic house hold use; the water consumption per capita per day (lpcd). The total consumptive water requirement was based on the 2013 CSA population projection of Ethiopia (see table 3.4).

The population data of CSA was based on woreda level. However, some of the woredas are not fully located in study area accordingly assumption was made based on the area of the wored in the catchment. Since many data are not available at a catchment level.

According to the report total projected rural catchment population in the year 2015 was **923,641** of which **466014 (50.5 %)** are male and **457,627 (49.5 %)** are female.

Table 3-4: Population Projections Based on projected population report of CSA (CSA, 2013)

No	Wereda	Region	No of kebelas in the cachment	Rural population			Urban population		
				Male	Female	Total	Male	Female	Total
1	Siraro_wereda	Oromiya	2	553	575	1128	0	0	0
2	kofela- wereda	Oromiya	4	14824	15022	29846	0	0	0
3	shala	Oromiya	4	5803	5871	11675	0	0	0
4	shashemena zuriya	Oromiya	22	50483	51148	101631	2673	2620	5293
5	Kokosa	Oromiya	1	4140	4460	8600	910	749	1659
6	Hawassa city adminstration	SNNPR	44	59421	56433	115854	149250	152264	301514
7	Hawassa zuriya wereda	SNNPR	25	72118	70758	142876	0	0	0
8	Boricha	SNNPR	21	68687	68422	137109	4993	4892	9885
9	Gorche	SNNPR	13	33371	32507	65878	0	0	0
10	Malga	SNNPR	23	61533	59882	121415	3878	3787	7665
11	Shebedino wereda	SNNPR	7	17842	17593	35435	0	0	0
12	Wendo_wereda	SNNPR	19	77239	74955	152194	22794	21289	44083
Total				466014	457627	923641	184498	185600	370098

The per capita consumption of the catchment rural areas was generally based on the water demand standard of second Growth and Transformation Plan of Ethiopia (GTP 2 – which goes from 2015-2020). According to GTP-2, the country rural water supply target was 25 liter per capital per day. However the Country could not attain full coverage at this level. The water demand was computed by total population multiplied by the water use rates.

3.10.5. Industrial water consumption

Industrial water demand includes the water required for factories and industries. The Lake Hawassa catchment is already a focal point for industrial and agro-processing including the textile, beverage, food processing, coffee washing, coffee processing, tanning, brewery, dairy, flour , ceramic, tobacco, soft drink factory, milk processing facilities, fruits processing units, meat processing unit and edible oil mills. The Hawassa municipality and national government have developed industrial zones and there are opportunities to develop agro-processing with joint ventures between the cooperatives (which can buy and assemble raw materials) and the private sector (which can provide capital and management skills).

Most of these factories didn't have recorded water consumption information and some of the factories have their own water source (e.g. ground water). The water consumption of these industries and factories was determined by directly from their water use or indirectly from their monthly or annual production. Small industries, especially in cities, are more likely to obtain water from public water supply.

3.10.6. Environmental flow requirements (EFRs)

Environmental water assume it is any water which supports or enhances natural ecological systems (Hamstead, 2007). Insufficient water availability for essential ecosystem functions and services can lead to ecosystem degradation with consequent impacts on overall water scarcity and human well-being (Falkenmark, 2004).

In order to supports or enhances natural ecological systems as well as the natural channel habitat associated to the historic flow regimes of the lake catchment, a certain reserve flow has to be maintained and could be considered as a sectoral consumption on its own.

In this study flow duration curve analysis naturalized or present-day historical flow records are analyzed over specific durations to produce curves displaying the relationship between the range of discharges and the percentage of time each of them is equaled or exceeded. For example in some cases the 90 percentile flow (Q90) may be set as the minimum environmental flow. This is the flow that is exceeded 90% of the time. An environmental flow that corresponds to low flow of 90 % exceedance of flow duration curve was used in this study.

4. RESULTS AND DISCUSSIONS

4.1. SWAT- WB model calibration and validation

4.1.1. Sensitivity analysis

The result of the sensitivity analysis showed that 9 flow parameters were sensitive to the SWAT-WB model. The overall sensitivity analysis result of this study revealed that the first ranked parameter is HRU parameter: the Soil evaporation compensation factors (Esco) which configured the depth of soil at which water can still evaporate from the soil. The second and the third ranked parameters also Soil related parameters: the soil available water content (SOL_AWC), and Depth from soil surface to bottom of layer (Sol_Z) in (mm). The fourth ranked parameter is Ground water related parameter: Groundwater revap coefficient (Gw_Revap), which is dimensionless coefficient controlling the rate of water movement between the root zone and the shallow aquifer. The sensitivity analysis output of the model shown in table 4.1.

In general the catchment hydrological modeling was found more sensitive to HRU and soil parameters. A description of these parameters with their effect is provided in the SWAT user manual (Neitsch et al., 2005).

Table 4-1: SWAT-WB most sensitive parameter

Parameter	Description	Sensitivity value	Class	Rank
Esco	Soil evaporation compensation factor	0.55	High	1
Sol_Awc	Soil available water content	0.20	High	2
Sol_Z	Depth from soil surface to bottom of layer (mm)	0.15	Medium	3
Gw_Revap	Groundwater "revap" coefficient	0.12	Medium	4
Ch_N2	Manning's n value for main channel	0.09	Medium	5
Alpha_Bf	Base flow alpha factor (days)	0.05	Medium	6
Ch_K2	Effective hydraulic conductivity [mm/hr]	0.02	Small	7
Gw_Delay	Groundwater delay [days]	0.02	Small	8
Sol_K	Hydraulic conductivity of the soil	0.02	Small	9

Tekle and Abebe, (2016) identified Seven sensitive SWAT-WB model parameters controlling runoff for Didessa Watershed in which (SOL_Z) depth from soil surface to bottom of layer in mm), (SOL_AWC) soil available water capacity, and (ESCO) soil evaporation compensation factor were the high sensitive parameter in runoff production.

4.1.2. Model calibration

The comparison of default simulation output with the observed value showed a clear difference between the simulation result and observed stream flow which necessitate model calibration. So many model runs were done by changing the model parameters values and different model results have been obtained during the process. Parameters that affect the model result were adjusted in order for simulated output to meet the observed flow. The model runs continued up to optimized parameters were achieved that give the best correlation between simulated and observed data sets using manual calibration technique. The final adjusted parameter values for Tikur Wuha sub catchments are presented in table 4.2.

Table 4-2: Calibrated value of SWAT-WB model parameter

No	Parameter	Description	Default Values	Calibrated Values
1	Esco	Soil evaporation compensation factor	0.95	0.75
2	Sol_Awc	Soil available water content	Varies	+25%
3	Sol_Z	Depth from soil surface to bottom of layer (mm)	Varies	+20%
4	Gw_Revap	Groundwater "revap" coefficient	0.020	0.04
5	Ch_N_2	Manning's n value for main channel	0.014	0.023
6	Alpha_Bf	Base flow alpha factor (days)	0.0480	0.90
7	Ch_K_2	Effective hydraulic conductivity [mm/hr]	0.000	150
8	Gw_Delay	Groundwater delay [days]	31	200
9	Sol_K	Hydraulic conductivity of the soil	Varies	+20%
10	EDC	Effective depth of the soil profile	0.995	0.015 – 0.9

Varies= to indicate the value varies by soil type and soil layer

The comparison of observed and simulated flow for calibration period indicated that there were good agreements between observed and simulated monthly flows. The hydrograph of calibration results are presented in figure 4.1.

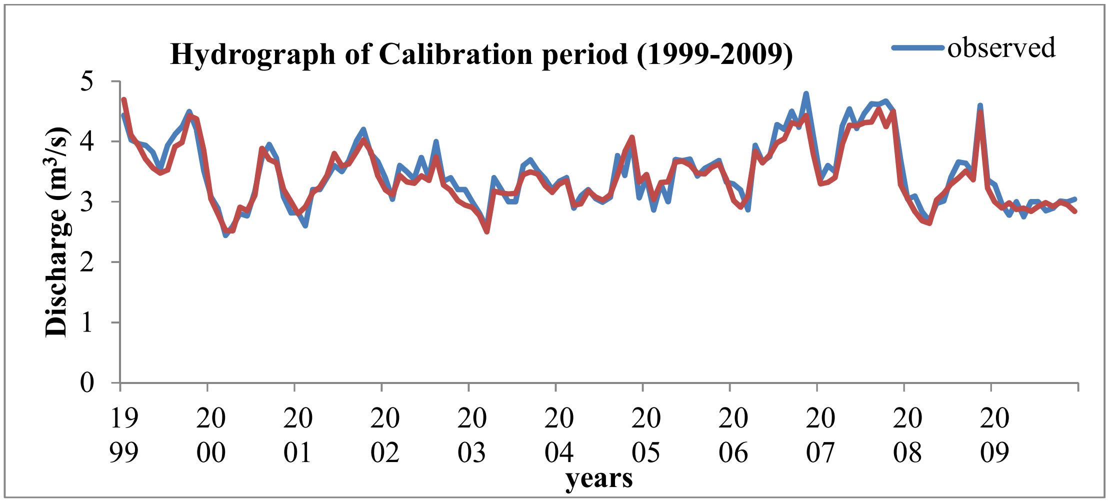

Figure 4-1: Hydrograph of the observed and simulated monthly flow for the calibration period.

As the hydrograph shown in figure 4.1, the model starts simulation with high estimates of the flow due to high precipitation during the years 1997, 1998 and 1999 which have 16%, 7%, and 12% above the catchments long term mean annual rainfall and Tikur wuha river discharge measured on these years is also 10-14 % higher than the long term monthly average. The overall simulation result of calibration period clearly showed a good performance in the hydrologic simulation.

The model performed well in reproducing the observations as evaluated through coefficient of determination (R^2) of 0.69 and Nash-Sutcliffe simulation efficiency (ENS) of 0.66. This depicts a good agreement between measured and simulated monthly flows.

4.1.3. Model Validation

The result of validation showed good agreement between the simulated and measured monthly flow with the R^2 value of 0.67 and ENS value of 0.65. The hydrograph of validation period shown in Figure 4.2, and indicates that the model underestimates pick flow in 2010, 2011,2012 and 2013 and also overestimate minimum flow in 2012.

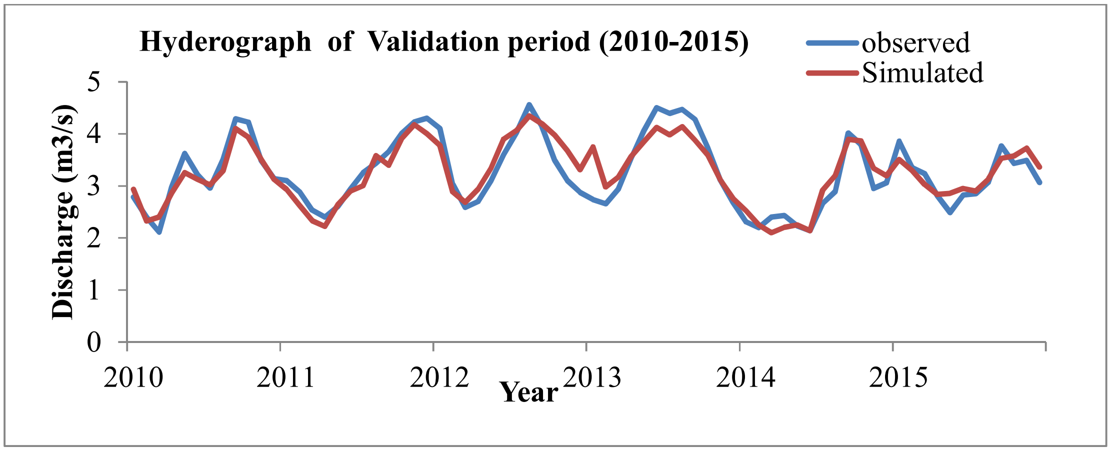

Figure 4-2: Hydrograph of the observed and simulated monthly flow for the validation period

In general comparison of observed and simulated flow for base period indicated that there was a good agreement between observed and calibrated flow yielding higher value of coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E_{NS}). The model performance can be judged as good if R^2 is greater than 0.6 and E_{NS} is greater than 0.65 (Setegn et al., 2008).

As per the studies carried out by various researchers applied in Ethiopia (e.g. Easton et al., 2010; Tekle and Abebe, 2016) the SWAT-WB model showed that a satisfactory agreement between monthly observed and simulated flow during caliberation and validation period measured by coefficient of determination which are greater than 0.6 and Nash-Sutcliffe efficiency greater than 0.53.

4.2. Prediction in the ungauged sub-catchments

Muleti, Wedesa-Kerama, WendoKosha and Shashemene-Toga sub catchments are ungauged. The calibrated model parameter values of Tikur Wuha sub catchment are transferred to these ungauged sub catchments based on HRU similarity. HRUs with the same land use, soil type and slope definitions are assumed to have similar hydrological behavior. The gauged Tikur Wuha sub catchment and other ungauged sub catchments were shown in figure 4.3 and similar HRUs on gauged and ungauged part of the catchment shown in figure 4.4.

Tegegne et al. (2013) similarly transferred calibrated and validated SWAT model parameters from the gauged sub catchments of Lake Tana (Gilgel Abay, Gumera, Rib and

Megech) to un-gauged part of Lake Tana catchment to estimate the ungauged flow contribution to Lake Tana water balance based on similarity of the hydrologic response unit (HRUs).

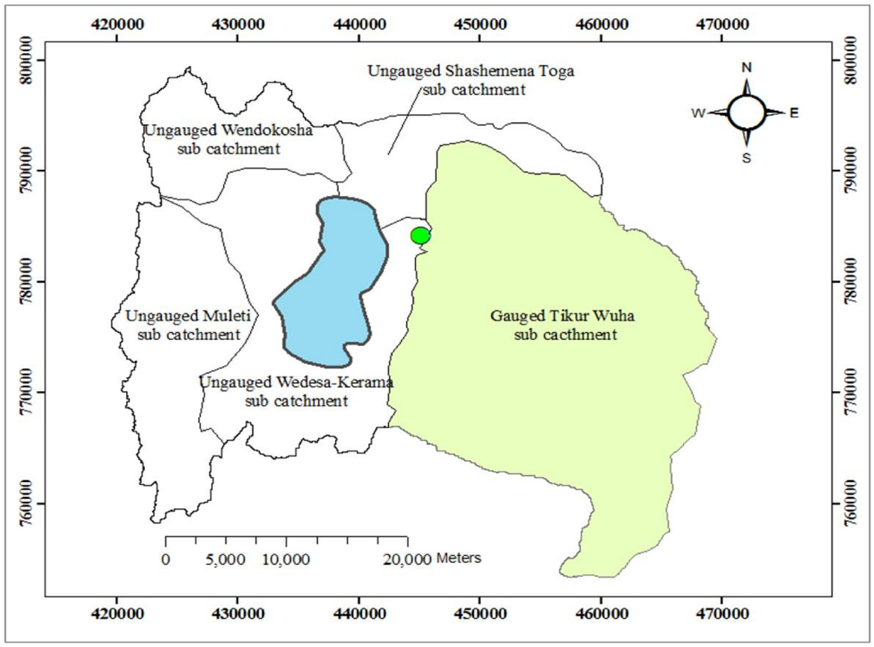

Figure 4-3: Map of gauged Tikur Wuha sub catchment and Ungauged part the Lake Hawassa catchment

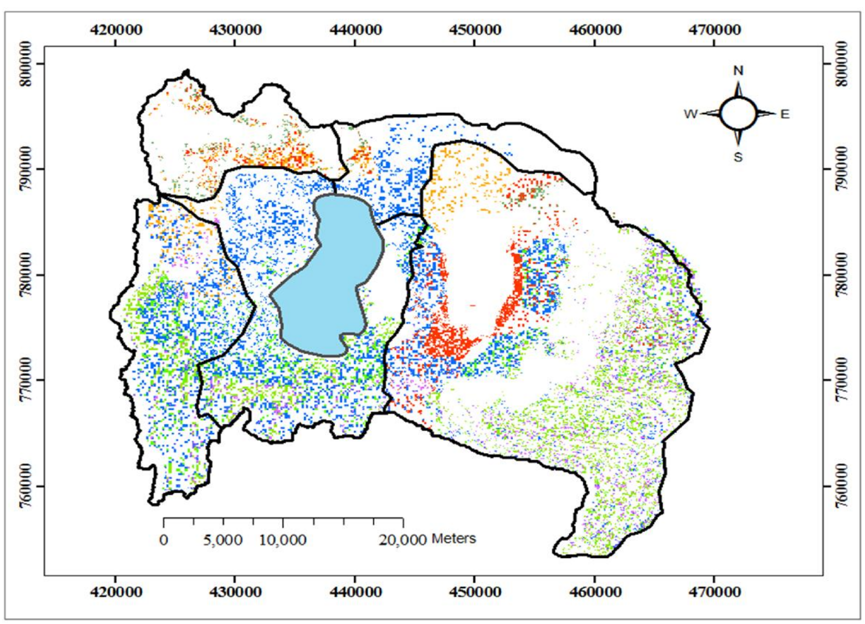

Figure 4-4: HRU similarity map of gauged and ungauged sub catchments of Lake Hawassa catchment

4.3. Water balance components of the Tikur wuha sub catchment

The water balance components rainfall, runoff, evapotranspiration and groundwater recharge can be effectively estimated through the simulation of the SWAT-WB model for the period of study.

After writing back the final calibrated model parameters values obtained from calibration process in to SWAT-WB model to simulate water balance components of the Tikur wuha sub catchment, the following results were found.

The annual rainfall of the sub catchment over the period 1999 to 2015 is 1036.6 mm/y and surface water runoff 227.37 mm/y and lateral soil flow is 62.56 mm/y. the total runoff found by the model in the sub-catchment area of 649.5 square km is 147.7 Mm^3/ y. The entire model output types, which have mean annual values shown in table 4.3

Table 4-3: Average annual water balances simulated for a base periods of 1999–2015.

Water Balance Components	Amount in (mm)
Precipitation; Precip	1036.6
Surface runoff ; Sur_Q	227.37
Lateral soil flow contribution; Lat_Q	62.56
Ground water contribution to streamflow; Gw_Q	38.58
Revap or shallow aquifer recharges	0.43
Deep Aquifer Recharges	236.9
Total water yield; Twyld	328.59
Percolation out of soil; Perc	255.82
Actual evapotranspiration; ET	708.2
Potential evapotranspiration; PET	1719
Transmission losses; Tloss	0.2

From the water balance components actual evapotranspiration contributed a larger amount of water loss from the sub catchment and total water yield is the amount of stream flow leaving the outlet of sub catchment during the time step.

4.4. Results of Lake Water balance

The main inflows into the lake were direct precipitation and stream flows while the outflows include evaporation, and groundwater outflow.

The mean surface area rainfall during the study period was 93.58 mm/month. The monthly lake surface evaporation was 138.65 mm/month. The mean surface runoff flowing in to the lake was 15.05 mm/month. The estimated net groundwater inflow obtained from SWAT-WB result was 12.90 mm/month. The estimated ground water outflow as a residual term in the continuity lake water balance equation is 45.80 mm/month which was greater than that of ground water inflow during the observation period.

After quantification of lake water balance components, simulation of the long term monthly (1999-2014) water balance of the lake modeled in Excel spread sheet program shows uncertainty in prediction of observed lake volume. This disagreement may due to high accumulation of silt in the lake and inaccurate determination of net ground water flow. Similar discrepancy results were reported by different pervious researches indicated that sharp rises in water level of Lake Hawassa had been occurred and it could not be explained in terms of the water balance components (Gebreegziabher, 2004; Ayenew and Gebreegziabher, 2006; and Belete , 2013). The simulated result was shown in figure 4.5.

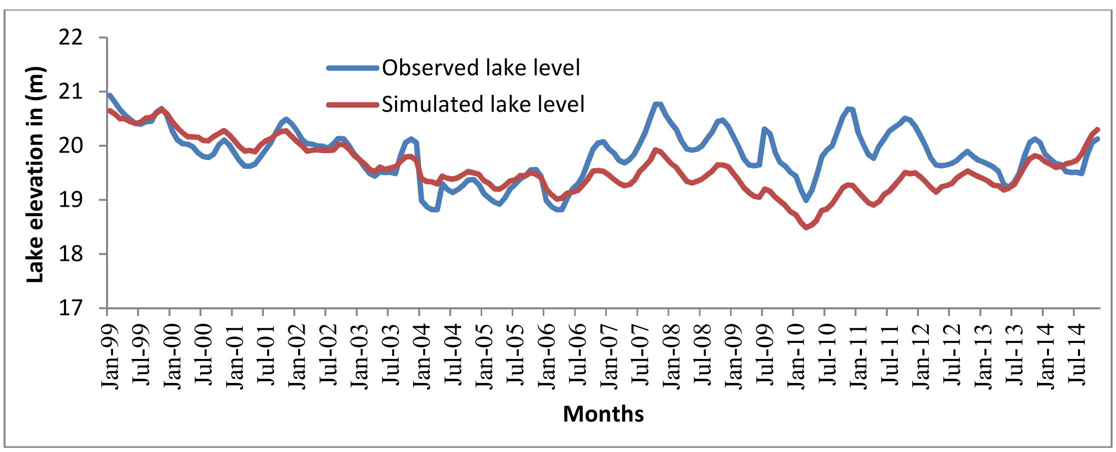

Figure 4-5: Results of lake level from 1999 – 2014.

From the result of monthly water balance average lake depth and the magnitude of net lake storage volume during the study period using the relationship between lake depth and volume developed by Gebreegziabher (2004) ware 20.84 m and 1017.51 Mm^3 respectively.

4.5. The Blue and Green water Availability

The Final fitted parameter values of the gauged Tikur Wuha sub catchment were transferred to ungauged part of Lake Hawassa catchment for correctly simulation of hydrological parameters of the catchment in the SWAT-WB model. The gauged Tikur Wuha River sub catchment and the ungagude part of Lake Hawassa catchment had the same HRUs definition from the minimum threshold level of 15% land use, 15% soil unit and 10% slope.

Using the calibrated model, the annual and monthly values of hydrological components of the cacthment simulated by SWAT-WB over the period 1999 – 2015, blue water flow (water yield), green water flow (actual evapotranspiration), and green water storage (soil water) were calculated for each subbasin and summed up for the catchment.The simulated values are presented in table 4.4 below.

Table 4-4: Average monthly values of Blue and Green water simulated for a base periods of 1999–2015.

Months	Blue water flow (mm)	Green water flow (mm)	Green water storage (mm)
Jan	11.689	23.362	42.535
Feb	7.419	24.298	39.517
Mar	13.625	63.19	54.471
Apr	24.102	90.539	54.373
May	40.378	100.647	45.83
Jun	38.926	76.874	41.764
Jul	35.119	72.258	49.029
Aug	32.432	72.341	61.896
Sep	41.226	65.834	72.828
Oct	53.563	57.261	62.874
Nov	45.853	35.636	45.097
Dec	25.667	24.021	40.837

The result of SWAT-WB showed that 500.24 Mm^3 of Blue water flow, Green water flow quantity of 954.86 Mm^3 and Green water storage quantity of 826.14 Mm^3 available annually. In addition the simulation of lake water balance indicates that 1017.51 Mm^3 net blue water storage is available in the lake and the total available blue and green water in the catchment was 3.3 billion meters cube per year. The overall result of the catchment blue and green water values were showed in fig 4.6.

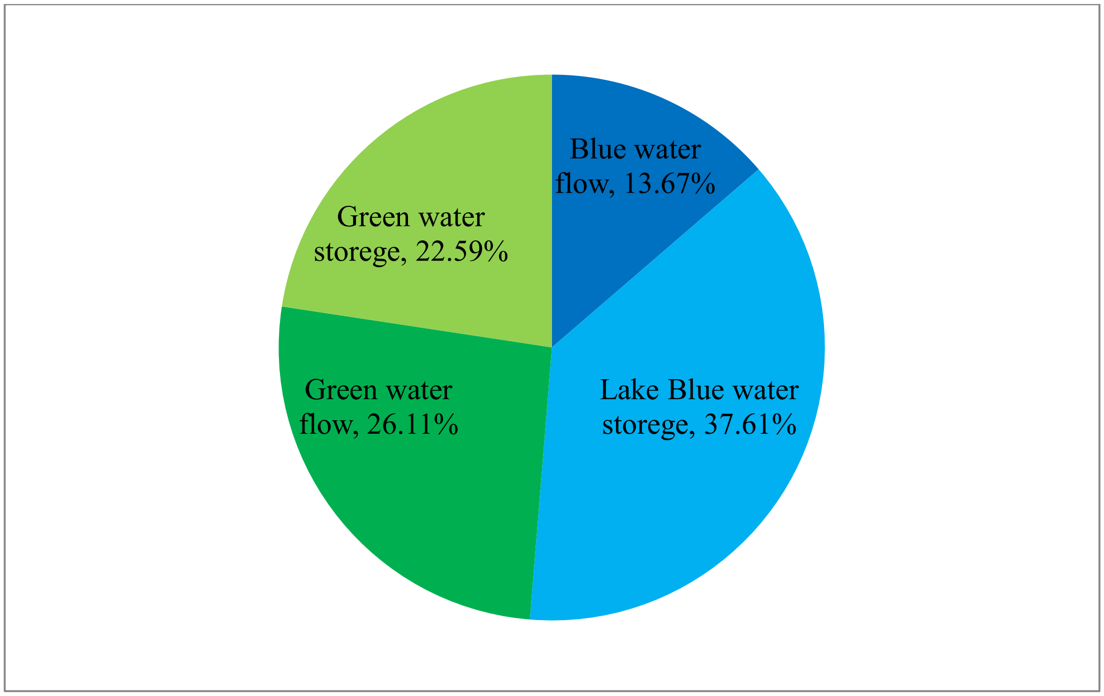

Figure 4-6: Average annual green and blue water balance in the Lake Hawassa catchment for simulation period

The proportionality relations between Blue and Green water obtained from this study, that is, Blue water flow of 13.67%, Blue water storage of 37.61%, Green water flow 26.11%, and green water storage of 22.59% are nearly similar to the same types of studies in Africa especially in Kenya and Burkina Faso. Such values can be considered reasonable for a humid tropical region, taking into account that Falkenmark and Rockstrom (2010) reported the global average of 35% for BW flow and 65% for GW flow, and 94.3% GW flow and 5.7% BW flow for Kenya (arid and semiarid climate) and Schuol et al.,2008 obtained 76-87% for GW flow at Burkina Faso (Western Africa, semi-arid climate, rainfall of 736 mm/year), and 46-47% for GW flow at Sierra Leone (Western Africa, monsoon climate, rainfall of 2219 mm/year).

In a distributed model, it is possible to view the output as it spatially varies across the catchment. Average annual values of blue water flow and green water simulated for a base period in sub-catchments and its variability across the catchment was displayed spatially in figure 4.7 and 4.8.

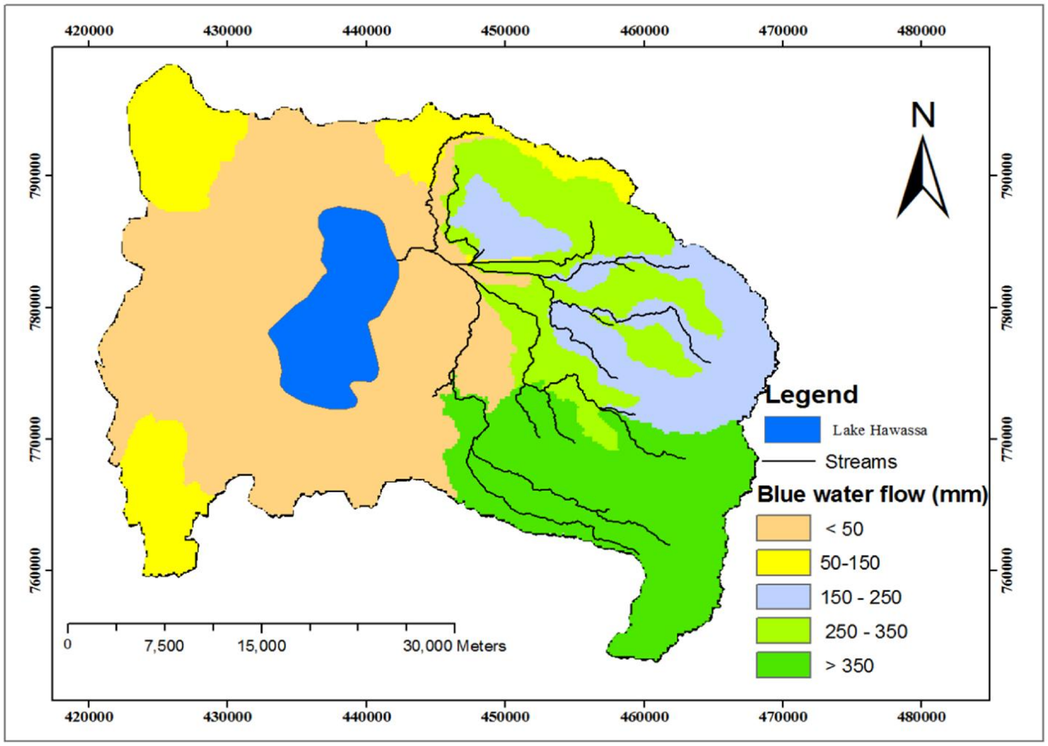

Figure 4-7: Simulated annual blue water flow at sub-basin level for the entire catchment

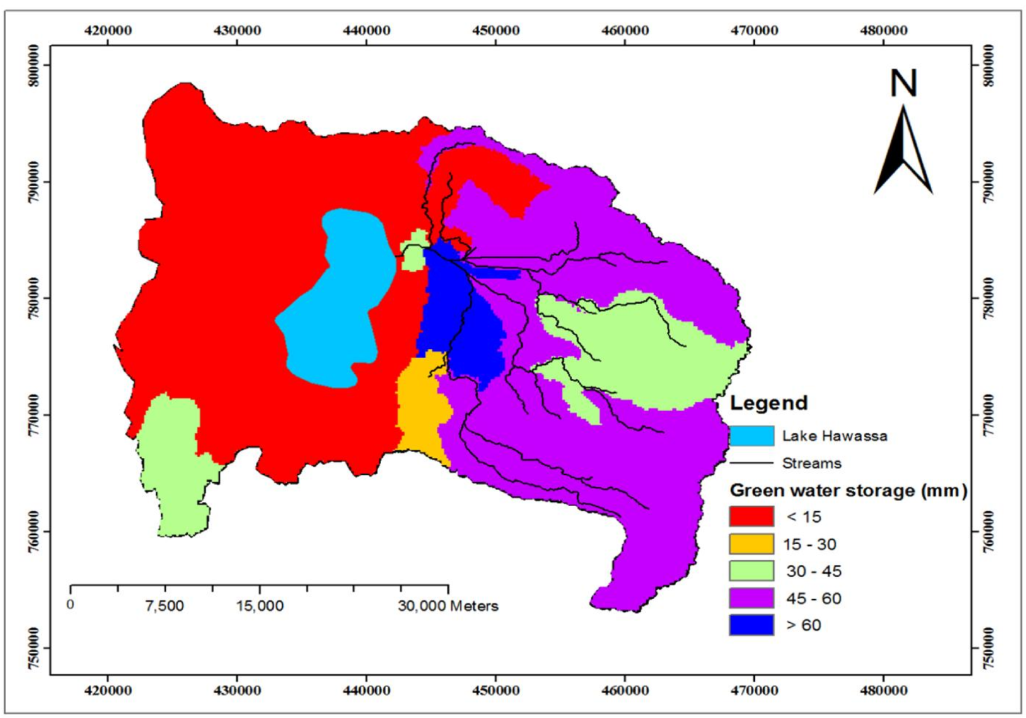

Figure 4-8: Simulated Green water storage at sub-basin level for the entire catchment

The amount of Blue and Green water resources simulated from each sub basins and the spatial distribution over the catchment shown in above Figures indicated that the eastern part of the catchment has a larger contribution to the blue water flow and green water storage. The spatial distribution of green water flow (ET) was relatively similar in the catchment. In general, significant differences existed in the spatial distribution of water resources components across the catchment.

Despite the spatial distribution, the seasonal variability of the freshwater availability is of great importance. Table 4.5 shows the seasonal average values for the three seasons.

Table 4-5: Seasonal water availability based on monthly average values over the period 1999 to 2015

Season	Duration	No of months	Blue water flow	Green water flow	Green water storage	Total fresh water
			mm/season	mm/season	mm/season	mm/season
Belg	Mar-May	3	78.12	254.37	154.68	487.17
Kiremt	Jun-Set	4	147.72	287.32	225.52	660.52
Bega	Oct-Feb	5	144.2	164.6	230.85	539.65

As shown in table 4.5, the blue water in the catchment was generally high in kiremt season and relatively low in belg season. The Green water flows are high in Kiremt season followed by Belg season. Green water storage is distributed more homogeneously in all seasons.

4.6. Results on Water consumption demands

The rapid increases in population, urbanization and industrialization have led to a significant increase in water consumption.

4.6.1. Agricultural water consumption

Source of water for agriculture in the catchment was both blue and green water resources. The CROPWAT model was used to estimate agricultural water consumption. The average annual agricultural water consumption was 142 Million m^3 of water, of which 14.69 % (21.1 Mm^3) was blue water and 85.31 %(120.9 Mm^3) was green water. The result shows that the overall the green water-use is much higher than blue water-use in the catchment.

The total calculated agricultural water consumption is shown in Table 4.6 and the catchment irrigation projects data and their location is shown in table form in appendix F.

Table 4-6: Annual water consumption of agriculture in the catchment

no	Seasons	Crop type	Representative crop	Area in ha	Planting date	Eff rain mm/ sea	Irr. Req. mm/ sea	Total consumption Mm^3	
								Green	Blue
1	1st irrigation	vegetables	Tomato	3435	20-Sep	106.8	350.3	3.7	12.0
2	2nd irrigation	vegetables	Tomato	3985	1-Feb	237.9	227.2	9.5	9.1
3	Bulg	Cereals	Barely	2600	20-Mar	203.4	0	5.3	0.0
		vegetables	Potato	3512	20-Mar	203.4	0	7.1	0.0
4	Summer	Cereals	Barely	5600	10-Jun	222.5	0	12.5	0.0
		vegetables	Potato	2700	10-Jun	222.5	0	6.0	0.0
5	Perennial crops			14500		529.7		76.8	
							Total	**120.9**	**21.1**

4.6.2. Livestock water consumption

Based on the projection data, Lake Hawassa catchment has a home for 622,322 cattle and 229,163 sheep and goats in 2015 and others, which is equivalent to 458,541.4 TLU. According to Seleshi (2010), the daily water consumption of one TLU is 25liter per day in Ethiopia. This was used for the determination of the water consumption. Based on these figure the annual water consumption is about 4.19 million cubic meters.

4.6.3. Urban water consumption

Ground water is the main source of water for urban water use in Hawassa town and other towns in the catchment. According to the data from Hawassa town water supply and sewerage office on average 12500 m^3 of water per day delivered from eleven boreholes, two springs and one river in 2015. The location and yield amount of these walls are presented in table form in appendix C-1 and river and spring water sources are presented in appendix C-2 and also the Hawassa city yearly water consumption of different sectors are presented in appendix C-3. There are Hotels, pensions, hospitals and garages they have their own wells, but the daily abstracted amount from the wells was not known because nearly all of them are ungauged. The water consumption of towns other than Hawassa town was done based on Growth and transformation program two (GTP- 2,2015) of Ethiopian standard with per capital water supply demand of 40 liter for category 1 town. The annual water consumption of these towns was about 0.8Mm3. Therefore the total urban water consumption in the catchment was 5.36 Mm3.

4.6.4. Rural domestic water consumption

The rural domestic water consumption was done based on Growth and transformation program two (GTP-2, 2015) of Ethiopian standard of water supply demand with per capital demand of 25 liter/day. According to the population projection data of CSA the total population in the catchment in the year 2015 was **923,641**. Based on this data the total annual rural domestic water consumption is about 8.43 million cubic meters.

4.6.5. Industrial water consumption

Nearly all large industries and factories in the Lake Hawassa catchment have their own ground water resource. Some of the industries have gauges to their wells and the water use of these industries presented in table in the appendix E-1. On the other hand the water use of industries they doesn’t have recorded information of water abstraction from their wells computed indirectly from their annual production level and presented in table in the appendix E-2. Based on these figures the total annual industrial water use in the catchment is about 2.3 million cubic meters.

4.6.6. Environmental flow requirement

In estimating the availability of water resources, consideration must be given to requirements for environmental flows to maintain the ecosystems of the river, to consider the obligations, and to maintain flow levels of downstream users.

The environmental flow in Lake Hawassa catchment in this study was determined from the flow duration curve corresponding to 90% exceedence of discharge. This flow is required /allocated to the environment along a Tikur Wuha river in order to fulfill the consumption of the channel ecosystem and downstream requirement.

The flow duration curve with 90 % exceedence shown in the figure 5.9, which is $1.25 m^3/s$, discharge is consumed by the environment. Environmental flow demands stay the same annually $39.45 Mm^3$ for the Tikur Wuha River.

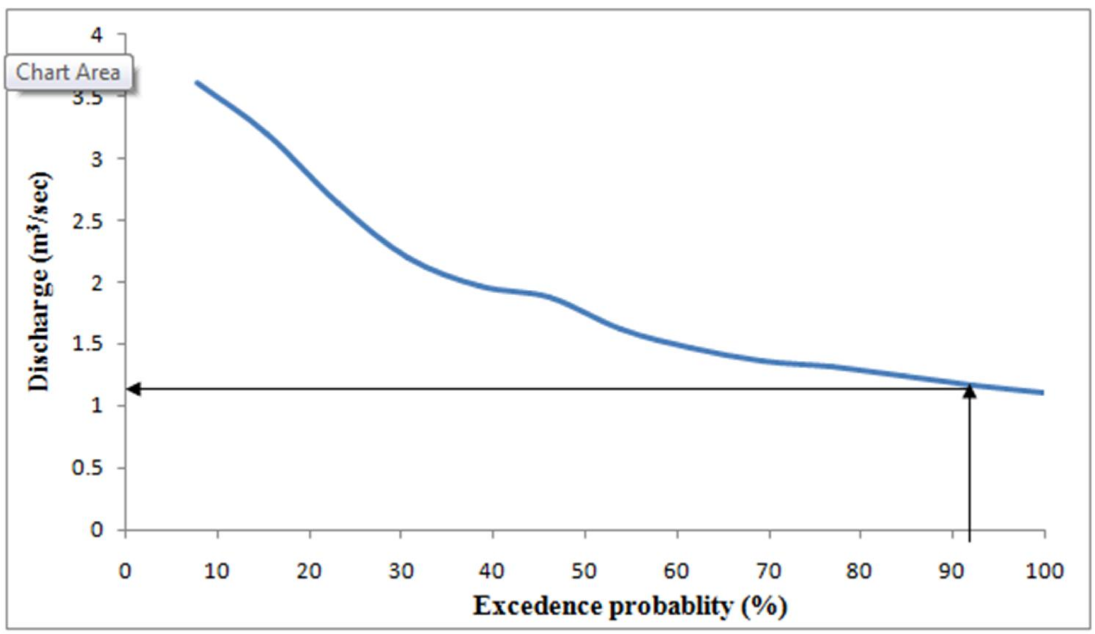

Figure 4-9: Flow duration curve of Tikur Wuha river

The comparison of current annual water consumption between different sectors reveals the clear dominance of agricultural water use dominancy over other water use sectors. That's the agricultural consumption takes 70 % of the total annual water consumption of the catchment. Such result is nearly similar to global average. It has recently been estimated that the approximately 69% of worldwide usage of water is for agriculture, mainly in the form of irrigation; 22% for industrial purposes, eight percent (8%) for domestic purposes, and one percent (1%) for recreational use (Kibona et al. 2009; Rosegrant et al. 2009; Cassardo and Jones 2011). Figure 4.10 shows the summary of water consumption demand share of different water use sectors in the catchment.

This information about catchment water users is crucial to develop an accurate management plan for water use or in planning and evaluating water resource projects.

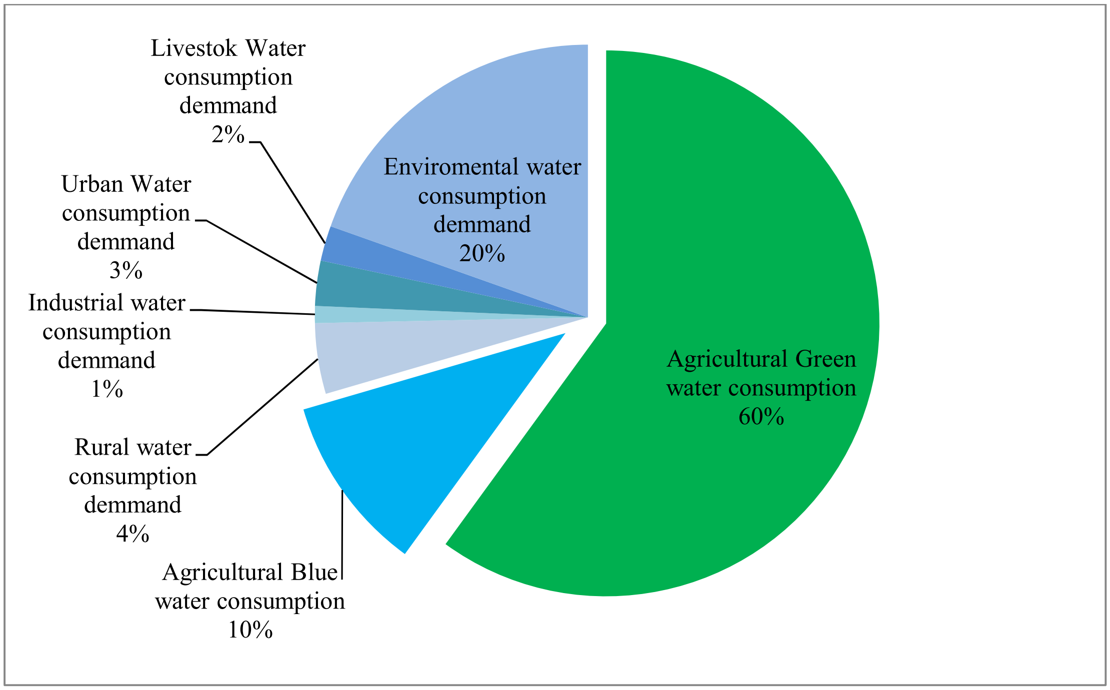

Figure 4-10: Annual water consumption demand share of water use sectors

The total water consumption for all water use sectors within the catchment is estimated to be 201.46 Mm^3 per year. Therefore, the water consumption in the catchment is around 6.11 % of the total fresh water available in the area, which is 3.3 billion cubic meters per year. Thus, the research output indicated that the catchment water resource is underutilized.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

In this study the fresh surface water resources (blue and green water flow and green water storage) of Lake Hawassa catchment was successfully simulated for the base period of (1999 to 2015) by the modified SWAT model SWAT-WB which models runoff from saturation-excess processes.

The SWAT-WB hydrologic model calibration and validation results evaluated based on Dato gauging station's observed monthly hydrological flow data showed that the model is able to simulate spatially distributed surface runoff generation in the sub catchment.

After modeling the gauged Tikur Wuha sub catchment for estimating water balance components, the calibrated parameters were transferred to un-gauged part of Lake Hawassa catchment based on hydrologic response unit (HRUs) similarity.

The long-term mean annual blue and green water flow and green water storage volume results obtained from model output found to be 500.24, 954.86 and 826.14 Mm^3 respectively. In addition the simulation of lake water balance showed that 1017.51 Mm^3 net blue water storage volume available in the lake. There existed significant differences in the spatial and seasonal distribution of blue and green water flows across the catchment.

The water consumption result shows that there is agricultural water consumption dominancy over other water users, accounting for 70% of the total consumption and the remaining 30% was for the other sectors. The overall consumption of water in the catchment is about 6.11% of the total Blue and Green water potential of 3.3 billion m^3 per year which indicates the catchment water resource is underutilized.

Generally, the result of this research revealed that the Blue and Green water potential of the catchment area was successfully quantified and the consumption demands of different water use sectors are still underutilized.

5.2. Recommendations

Based upon the finding of this study, the following recommendations were set forth. These are:

- Since there existed plenty of water resource in the catchment with respect to the Blue and Green water, the concerned body should develop effective water resources development and management plan to utilizations the resource in sustainable way.
- Also the water consumption level in the area is still very small so further investigation is essential to use the available water resource potential of the catchment.

Upon the realization of this study, the researcher had encountered the following constraints.

- One of the constraints in conducting this research work was lack of statistical data on catchment basis. This makes difficult to see the variation of water consumption results in the sub catchments.
- Since the Model prediction output depends on the quality of input data. The stream flow data used for this study were from old rating curve equation developed during gauge installation and not enough to represent the actual recent one. Therefore, there existed possibility of discrepancy between actual flows recorded and simulated flow. Hence, responsible bodies should give due attention to the recording of flow measurement and developing of a new rating curve equation.
- The other technical modeling problem in need of further research and improvement was related to lake water balance, determination of net ground outflow and catchments ground water storage potential.

In general, the SWAT-WB model performed well in modeling the hydrology of saturation excess hydrology. Therefore, researchers are beneficial if they want to model catchments with saturation excess runoff process as surface runoff generation method.

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7. APPENDIXES

APPENDIX A: Weather generator input parameters for SWAT-WB

TMP_MAX	Average daily maximum temperature in month [°C]
TMP_MIN	Average daily minimum temperature in month [°C]
PCPMM	Average monthly precipitation [mm]
PCPSTD	Standard deviation
PCPSKW	Skew coefficient
PR_W1	Probability of a wet day following a dry day
PR_W2	Probability of a wet day following a wet day
PCPD	Average number of days of precipitation in month
SOLARAV	Average daily solar radiation for month (MJ/m2/day).
DEWPT	Average daily humidity in month [%]
WND AV	Average daily wind speed

	TMP_MAX	**TMP_MIN**	**PCPMM**	**PCPSTD**	**PCPSKW**	**PR_W1**	**PR_W2**	**PCPD**	**SOLARAV**	**DEWPT**	**WND AV**
Jan	28.91	11.79	29.58	4.26	7.96	0.12	0.45	5.4	21.21	11.94	0.75
Feb	30.31	11.96	26.24	3.69	7.04	0.11	0.44	5.05	22.75	11.34	0.77
Mar	29.69	13.26	80.37	5.43	3.89	0.26	0.69	14.65	22.41	12.96	0.73
Apr	28.58	14.26	108.17	7.38	3.6	0.4	0.66	17	20.5	15.34	0.7
May	27.38	14.49	117.68	7.43	3.11	0.41	0.67	17.8	20.03	15.99	0.78
Jun	25.84	14.52	108.14	7.6	3.8	0.54	0.53	16.55	18.4	15.13	0.95
Jul	24.75	14.67	130.95	8.28	3.28	0.52	0.66	19.5	16.71	15.06	0.88
Aug	25	14.68	125.42	8.19	5.5	0.59	0.67	20.7	17.48	15.3	0.83
Sep	25.69	14.12	124.47	6.77	3.66	0.68	0.74	22.7	18.56	15.66	0.65
Oct	26.98	13.04	70.33	5.25	4.31	0.23	0.68	13.95	19.73	14.3	0.56
Nov	28.08	11.15	37.63	4.96	7.99	0.11	0.53	5.95	20.37	11.72	0.63
Dec	28.09	10.62	22.51	3.19	7.09	0.09	0.38	4	21.02	11.02	0.71

APPENDIX B: Soil types and SWAT-WB soil database parameters

SNAM	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE	SOL_Z1	SOL_BD1	SOL_AWC1	SOL_K1	SOL_CBN1	CLAY1
MOANDOSOLS	2	B	1000	0.5	0.5	loam	300	1.43	0.14	9.27	3.71	26
HPLUVISOLS	2	B	1000	0.5	0.5	sandy clay	300	1.42	0.11	16.39	0.6	21
EUFLUVISOLS	2	B	1000	0.5	0.5	loam	300	1.33	0.13	13.5	0.73	23
VTANDOSOLS	1	A	1000	0.5	0.5	Sandy loam	300	1.48	0.15	73.85	1.48	6
LTLEPTOSOLS	1	D	300	0.5	0.5	clay loam	300	1.3	0.17	7.78	0.39	28
EUVERTISOLS	2	D	1000	0.5	0.5	Clay	300	1.3	0.125	1.02	1.07	54
CHLUVISOLS	2	B	1000	0.5	0.5	sandy clay	300	1.45	0.12	8.73	0.63	27
SWAMP	2	B	1000	0.5	0.5	sandy clay	300	1.45	0.12	8.73	0.63	27
WATERBODIES	1	D	25.4	0.5	0.5		25.4	1.72	0	260	0	0

SILT1	SAND1	ROCK1	SOL_ALB1	USLE_K1	SOL_EC1	SOL_Z2	SOL_BD2	SOL_AWC2	SOL_K2	SOL_CBN2	CLAY2	SILT2	SAND2	ROCK2	SOL_ALB2	USLE_K2	SOL_EC2
36	38	1	0.1	0.26	0	700	1.42	0.14	7.76	1.55	28	35	37	1	0.15	0.23	0
25	54	1	0.08	0.23	0	700	1.51	0.12	8.69	0.26	27	24	49	1	0.23	0.35	0.06
33	44	1	0.11	0.22	0.1	700	1.4	0.13	12.69	0.32	23	31	46	1	0.22	0.28	0.1
26	68	1	0.22	0.13	0.1	0	0	0	0	0	0	0	0	0	0	0	0
29	43	32	0.1	0.25	0.1	0	0	0	0	0	0	0	0	0	0	0	0
25	21	1	0.22	0.2	0.1	700	1.58	0.11	0.91	0.56	56	24	20	1	0.27	0.24	0
22	51	1	0.19	0.2	0	700	1.5	0.12	3.94	0.35	34	21	45	1	0.22	0.27	0
22	51	1	0.19	0.2	0	700	1.5	0.12	3.94	0.35	34	21	45	1	0.22	0.27	0
0	0	0	0.23	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX C-1: List of Hawassa town water supply Bore holes

S. No .	Location	Well Name	GPS Coordinate			Well depth	source	Yield (lit/sec)
			Northing	Easting	Elevation (m)			
1	Gara Riqata Kebele	Gara Riqata #1,	447761	771220	1723	96 m	Bore hole	30
2	Gara Riqata Kebele	Gara Riqata #3	448467	771909	1721	125 m	Bore hole	30
3	Near Treatment Location	Treatment BH	447465	768772	1721	107m	Bore hole	7.7
4	Abella Wondo	Abella Wondo #1 (Old),	446393	770925	1729	58m	Bore hole	7
5	Abella Wondo	Abella Wondo #2 (Old),	447130	770258	1750	53m	Bore hole	6.0
6	Abella Wondo	Abella Wondo School	446375	770333	1741	163m	Bore hole	13
7	Qarara	Qarara	441352	770743	1762	193 m	Bore hole	7
8	Mette Well	Mette well #1 (Old	445607	770648	1722	50m	Bore hole	12.8
9	Mette Well	Mette well #2 (Old),				50m	Bore hole	7.3,
10		Mette well #2(new)	445303	770493	1727	204m	Bore hole	16 - 22
11	Gemeto Gale	Gemetto 1 New	445269	773012	1701	70m	Bore hole	30
12	Yuwo - P1	P - # 1	449214	771791	1711	200 m	Bore hole	50
13	Yuwo - P2	P - #2	449360	770943	1705	200 m	Bore hole	50
14	Yuwo - P3	P - #3	449976	771497	1705	200 m	Bore hole	50
15	Yuwo -P 4	P - #4	449926	770917	1714	200 m	Bore hole	50

16	Gara Riqata - P5	P - #5	447977	771948	1714	176 m	Bore hole	50
17	Gara Riqata-P6	P - #6	448525	772643	1701	200 m	Bore hole	50
18	Gara Riqata Kebele	Gara Riqata #2 (E-2),				107 m	Bore hole	30
19	Rural,	Rural BH	453052.55	769351.5		96m	Bore hole	4
20	Abella Wondo	Abella Wondo #2	44717124	770245	1745	95m	Bore hole	12.28
21	Abella Wondo	Abella Wondo #1 (New)	446365	770929	1724	150m	Bore hole	
22	Gemeto	FTC				….	Bore hole	25
23	Bashima	Bashima Water BH	443886	771378	1719		Bore hole	25
24	Gemeto Gale	Gemetto 2 New	445269	773012	1701	185m	Bore hole	73.35
25	Gara Riqata Kebele	Gara Riqata New	448118	772982	1705	175	Bore hole	75
26	Alamura,	BOKO Alamura	446375	770333	1741		Bore hole	17.75

APPENDIX C-2: List of spring and river water sources for Hawassa town

S.No.	Ref_ Location	Well Name	GPS Coordinate			source	Yield (lit/second)	Status
			Northing	Easting	Elevation			
1	Ambo	Ambo developed spring well	4531338	785238	1701	Spring	50	Functional
2	Loke	Loke developed spring well	436890	771918	1694	Spring	13	Functional
3	Bashima	Bashima Water Well	444669	770817	1723	Spring	6	Functional
4	Kedo River	Kedo river Treatment plant	451701	766610		River	38.8	Functional

APPENDIX C-3: Annual water consumption of different sectors in Hawassa city

Time	Commercial (m^3)	Domestic (m^3)	Public (m^3)	Government (m^3)	Industry (m^3)	Bono (m^3)	Total (m^3)
2008	483,776	678,747	91,355	170,299	133,378	-	1,557,555
2009	324,425	431,044	55,957	112,471	100,619	-	1,024,516
2010	556,739	834,415	203,852	185,125	114, 363	-	1,780,131
2011	651,255	1,092,074	104,810	150,147	115,294	-	2,113,580
2012	721,271	1,281,139	240,697	121,139	126,447	-	2,490,693
2013	741,256	1,419,237	333,997	142,146	101,802	74,207	2,812,645
2014	775,891	1,677,000	162,391	386,942	134,788	154,351	3,291,363
2015	771,598	1,948,617	164,370	399,421	110,635	204,725	3,599,366
2016	759,853	2,270,599	149,463	407,294	102,475	202,798	3,892,482
2017	745,230	2,471,437	183,334	456,847	78,902	174,851	4,110,601
2018	720,167	2,608,327	125,304	346,285	66,671	133,881	4,000,635

APPENDIX D: Hawassa Towns Hotels and institutions having their own well

No	Name of Hotel	Northing	Easting	Elevation	source of water	depth	Daily consumption (m3)	pump power	pumping Hour	Annual consumption
1	HUB	444130	778901	1716	Well		15	2.7	1.5	5475
2	Africa ug	441409	779862	1684	Well	12	141	7.5	24	51465
4	Haila Resort	442380	782311	1702	Well	180	220.32	18	3	80416.8
5	osis Hotel	440582	778943	1699	Well	16	4	3	24	1460
6	osis Hotel	440576	779002	1696	Well	12	3.5	2.2	24	1277.5
7	Operational midroc	440276	778997	1689	Well					
8	Lewi resort	444016	778871	1693	Well	18	38.62	0.9	16	14096.3
9	Tadesse Engory	441401	779209	1691	Well	50	35	11	24	12775
10	Rori	444183	778608	1718	Well	60	40	7.5	1	14600
11	Gezahge and elfinesh	444281	777817	1740	Well	80	40			14600
12	Lewi menaheriya	443106	779159	1740	Well	50	5	2.5	2	1825
13	Lewi Campus	443927	780054	1708	Well		10	1.5	3	3650
14	Haroni hot	441977	779202	1698	Well	30	20	14	4	7300
15	Atenet buld	442383	778732	1712	Well		10			3650
16	lewi piassa	441863	779360	1706	Well	53	5	1.5	0.25	1825
17	Messay hotel	442695	778446	1714	Well	50	0			0
18	South star	442892	779273	1789	Well	45	90			32850
19	South spring	442892	779273	1729	Well		9		3	3285
20	beshu complex	443340	777668	1721	Well	46	10			3650
21	Betibeb pension	444138	779051	1720	Well	24	0			0
22	Progress hotel	440276	778997	1689	Well	8	40	3		14600

APPENDIX E-1: Factories having their own well in Lake Hawassa Catchment

No	Factory name	Northing	Easting	Elevation	source of water	depth (m)	pump discharge (lit/sec)	Daily consumption (m3)	pump power	Annual consumption (m3)
1	Elfora	444465	784223	1682	Pump from river		125		22	1642500
		447019	786148	1700	Well	84	25	4500	35	0
3	Seramic Factory	440334	782236	1714	Well	36	8.5	10	7.5	3650
		443728	782166	1707	Well	36	5	10	7.5	3650
4	Hawassa electric pole factory	445175	777931	1734	Well	80	1.1	40	3	14600
5	Agro stone factory	445392	777594	1738	Well	70	0.5	30	7.5	10950
6	Chipud factory	445000	777022	1731	Well		1.74	150	7.5	54750
7	Hawassa flour factory	443460	782565	1742	Well	45		18	4	6570
8	Selam water packing Factory	462524	792879	2171	Well	198	5	360	20	131400

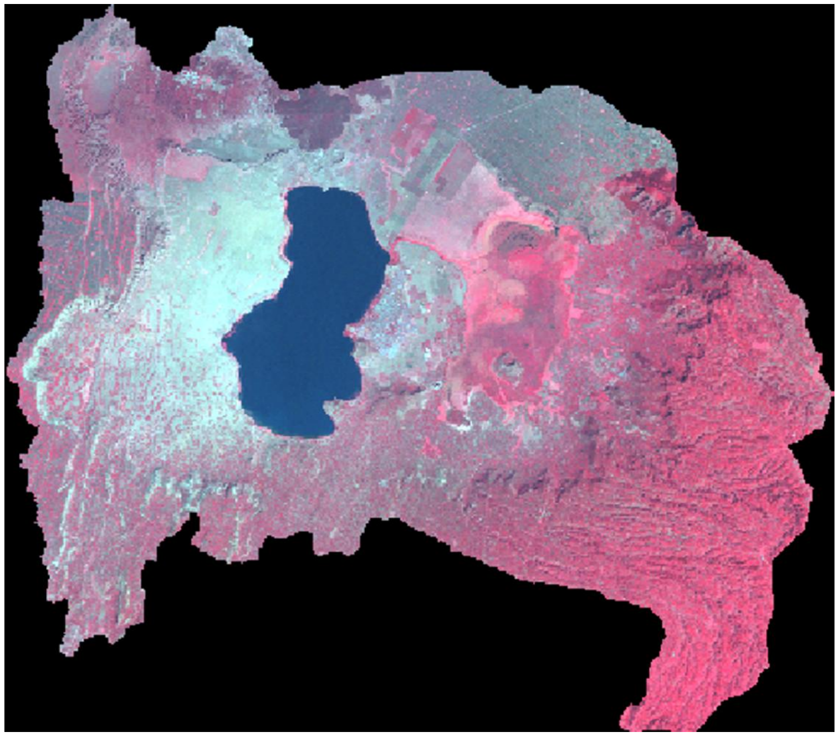
APPENDIX E-2: Factories water consumption based on annual production level in Lake Hawassa Catchment

No	Factories	Source of water	Production level	Liter required to produce a unit	Annual consumption in Mm3
1	BGI Hawassa	2 wells	5000000lit/year	20	0.1
2	Pepsi Hawassa	3 wells	60,000 lit/hr	5	2.592
3	Etabe soap factory	2 wells	12,000 kg/ day	3	0.0132
4	Hawassa textile factory	1 well	120 ton/ year	10,000	1.2
5	Hawassa industrial park				new

APPENDIX F: Irrigation sites and their location in Lake Hawassa catchment

No	Wereda	kebela	Water Source	Command area (ha)	Crop type	GPS location		
						Latitude	Longitude	Elevation
1	wendo south	Wosshama soyama	wosha river divertion	400	Vegitables	461014	783077	1922
2	wendo south	Baja fabrica	Wedesa river	593	Vegitables	417095	772138	1879
3	wendo south	Wosha kechema	Wedesa river	52	Vegitables	460338	779440	1955
4	wendo south	Edo	Abosa river	285	Vegitables	453772	770620	1814
5	wendo south	Chuko	Gomosha	100	Vegitables	457318	774697	1795
6	wendo south	Aruma	Afina River	19.25	Vegitables	452607	769937	1790
7	wendo south	Wosha soyama	Worka River	120	Vegitables	459832	782723	1846
8	wendo south	Wotera Kechama	Worka River	125	Vegitables	4559832	762723	1986
9	wendo south	Chuko	Dilla Spring	47.5	Vegitables	459036	776377	2065
10	wendo south	Abaya	Dobido spring	62	Vegitables	458901	776464	1990
11	wendo south	Baja fabrica	Dubicho spring	60	Vegitables	455892	771898	1968
12	wendo south	Aruma	Spring	70	Vegitables	451162	770280	1703
13	wendo south	Abaya	Han Damo spring	76.5	Vegitables	460699	777729	1978
14	wendo south	Baja fabrica	Fiewuha Spring	45	Vegitables	456479	771767	1907
15	wendo south	Aruma	Lakicho Spring	15.75	Vegitables	451263	769665	1968
16	wendo south	Chuko	Dobicho Spring	12.5	Vegitables	458949	776343	1979
17	wendo south	Yuwo	Shallow well	1.25	Vegitables	450180	771567	1708

APPENDEX G-1: Lake Hawassa catchment Landsat images (2014)



APPENDEX G-2: Lake Hawassa catchment Thiessen polygon and location of *meteorological* stations