MODELING WATER RESOURCES USING WEAP MODEL FOR EFFECTIVE WATER MANAGEMENT: A CASE STUDY IN LEGEDARA RIVER CATCHMENT, SNNPR, ETHIOPIA

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HENOK MEKONNEN ARAGAW

HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

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BY: HENOK MEKONNEN ARAGAW

MAJOR ADVISOR: BROOK ABATE (PhD)

CO - ADVISOR: SIVASAKTHI (PhD)

THESIS SUBMITTED0 TO THE

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STATEMENT OF AUTHOR

First, I declare that this thesis is my original work and that all sources of materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for MSc degree at Hawassa University and I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

Name: HenokMekonnenAragaw

Signature: ____________________

Place: Hawassa University, Hawassa, Ethiopia

E-mail: henokm54@gmail.com

Date of Submission: ________________

BIOGRAPHICAL SKETCH

The author was born in South Wollo, Dessie of Amhara Region, Ethiopia on January 12, 1992 G.C. He attended his elementary junior and senior secondary schools at Getara and Hote Elementary Junior and Senior Secondary School respectively. After completing secondary school, he joined Mekelle University in September 2010 and graduated in July 2014 with BSc. degree in Water Resources and Irrigation Management. Soon after graduation, the author was employed by Dilla University. In October 2015, he joined Hawassa University to pursue his postgraduate study in Water Resources Engineering and Management.

DEDICATION

This thesis is dedicated to my mother AbebechAssen whom I have lost in the early stage of my childhood and to my father MekonnenAragaw whoshoulder the double role as mother and father after her departure to grow up his Sons.

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LIST OF ABBREVIATIONS AND ACRONYMS

AET	Actual Evapotranspiration
BMC	Billion Meter Cubic
CSA	Central Statistical Agency
DEM	Digital Elevation Model
DSS	Decision Support System
ETM	Enhanced Thematic Mapper
ENS	Nash-Sutcliffe Efficiency
ETo	Reference evapotrainspiration
FAO	Food and Agricultural Organization
FDC	Flow Duration Curve
GIS	Geographic Information System
GPS	Global Position System
GTP	Growth and Transformation Plan
GWP	Global Water Partnership
GZWMEO	Gedeo Zone Water, Mineral and Energy Office
HBV	HydrologiskaByransVettenbalansvadelning (Hydrological Bureau water balance section)
IWRM	Integrated Water Resources Management
Kc	crop coefficient
Km^2	Kilometer square
m	meter
m.a.s.l	meter above sea level
mm	millimeter
MCM	Million Cubic Meter
MoWR	Ministry of Water Resources
MoWE	Ministry of Water and Energy
MULINO-DSS	Multi-Sectoral Integrated and Operational Decision Support System
Ptot	Precipitation
Pccs	Physical catchment characteristics

Peff	Effective Precipitation
RIBASIM	River Basin Simulation Model
R^2	Coefficient of Determination
RVE	Relative Volume Error
SEI	Stockholm Environmental Institute
SNNPR	South Nation Nationality and Peoples Region
SWAM	Simplified Water Allocation Model
SWAT	Soil and Water Assessment Tool
USDA	United States Department of Agriculture
WBalMo	Water Balance Model
WEAP	Water Evaluation and Planning
WHO	World Health Organization

ABSTRACT

Water is the life blood of all living things yet its availability and management is not well understood and quantified at the catchments scale. Legedara River catchment water resources availability is not well known since the catchment is ungauged and also the water demands within the catchment is not quantified and properly allocated. This study attempted to model the water resources of Legedara river catchment in SNNPR for effective water management through scenario analysis using WEAP model.Hydro-meteorological, spatial, and water demand data were the basic inputs to the model. FAO-Rainfall-Runoff (Simplified Coefficient) method was used to estimate runoff of Legedara River catchment by transferring calibrated model parameters from gaugedWaleme River catchment. However, before transferring calibrated model parameters different procedures were done, since selection of representative catchment, modeling of gauged catchment and calibration and validation. Catchments areal rainfall and reference evapotranspiration are estimated by Thiessen Polygon method and Penman Monteithmethod respectively. Domestic, industrial and environmental water requirements were estimated using WEAP model. Current situation of water demands for the selected water users were simulated. Five different scenarios for future water demands were developed and in addition to these climate scenario was developed and evaluated. During the model setup, all demand sites were assigned equal priority. As a result of parameter derivation hydro-meteorological Waleme River catchment is almost similar to Legedara River catchment. The model calibration and validation results were found satisfactory for the gauged catchment (ENS = 0.81; R^2 = 0.86 and RVE = -2.64% for calibration and (ENS = 0.77; R^2 = 0.81 and RVE = -7.73% for validation). The water balance components of Legedara River catchment were estimated and mean annual values of rainfall and reference evapotranspiration found to be 1316.42mm and 1142.07mm, while the actual evapotranspiration and runoff constitutes; 538.78mm and 778.65mm respectively. The modeling result revealed that, all the selected demand sites satisfied fully in the current situation and for reference scenario, scenario one, two and four, even though the remaining river flows for the months of December, January and February were almost zero after deduction. However, the result of catchment water resources and demands showed that at the last year of scenario three (2040), there will be a 26.71MCM, i.e., 36.17%, reduction in the total annual flow of Legedara river catchment.Moreover, it was found in the catchment that it is having unmet demands in scenario three. Nonetheless, it was shown that environmental flow requirement of 14.77MCM will be fully delivered at the outlet of Legedara River catchment. Hence, no absolute scarcity of water would develop. In scenario five, the simulating value showed that, increase and decrease of current mean monthly rainfall values by 10% and 5% have an impact on increase or decrease of catchment runoff.Further researches on groundwater availability were also suggested to meet the unmet demands.

***Keywords**: WEAP, Legedara River,Waleme River,SNNPR, Water balance, Water demand, Scenario analysis,*

1. INTRODUCTION

1.1. Background and Justification

Nowadays water resources are a critical component for any type of socio economic development all over the world. Thus its availability and use is the key determinant of economic growth and social prosperity. However, water is a finite resource and its use for one purpose reduces its availability for other purposes. Competing water needs trigger conflicts between disparate water users such as the rich and the poor, or between different sectors and regions, such as domestic and agriculture, agriculture and industry, agriculture and fisheries, upstream and downstream, rural and urban areas, and fisheries and flood control. Increased demand for water stemming from population and economic growth and ecosystem services on the one hand, and the problem of water management in flood control situations on the other, have posed significant challenges for the planning and allocation of its uses among competing demands (Abdullahi, 2015). Maximizing net returns with the available resources is of the utmost importance, but doing so is a complex problem, owing to the many factors that affect this process (climatic variability, irrigation system configuration, production costs and subsidy policies) (Uitto, 2004; Conway *et al.*, 2009). Many regions are facing formidable freshwater management challenges, as well as allocation of limited water resources, environmental quality and policies for sustainable water use are issues of increasing concern (Stockholm Environmental Institute (SEI), 2016).

Earth's fresh water is stored in reservoirs such as glaciers and icecaps, oceans, surface water, underground, and in the atmosphere. The replenishment rate of this water per annum is used to determine a country's fresh water available. Earth's water is constantly in motion, passing from one state to another, and from one location to another, which makes its rational planning and management a very complex and difficult task under the best of circumstance (Turner *et al*, 2004).

Water resource management is becoming increasingly complex and challenging to managers and policymakers due to the increase of multiple stress such as climate change, demographic change and the rise of energy demand (Sun *et al.*, 2008). Many regions are facing formidable freshwater management challenges which dared by rapid growing urban population and poor managements of the existing water resource (Micheal, 2013).The current challenges facing the water supply sector are keeping pace with net population growth, closing the coverage and service gap and ensuring sustainability of existing and new services with improved quality of services (Helena *et al.*, 2010).

Despite, Ethiopia is endowed with abundant surface and ground water resource, the water supply sector is the least developed and is mostly characterized by service deficiency of physical infrastructure as well as by inadequate management capacity to handle policy and regulatory issue and to plan, operate, and maintain the services (Seleshi*et al.,* 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/wetlands. However, the water scarcity and inadequacy is the main feature of the country today (Seleshi*et al.,* 2007).

Legedarariver catchment is located in the Rift Valley Basin.Different water users (i.e., rural, urban, industrial) are present in the catchment.The catchment is endowed with plenty of surface and ground water resource in and around. The water resources of the river have been serving as sources for domestic and industrial water supply.Nevertheless, sustainable water resources management in the catchment is constrained by a number of uncertainties.Firstly, the available waterresource of the catchment is not well known. Secondly, the water demands in the catchment are not quantified.

Therefore, in order to ensure the availability of sufficient quantity and good quality of water, it becomes almost imperative in a modern society to plan and build suitable water supply schemes which may provide potable water to the various section of the community in accordance with their demands and requirements (Garg, 2010).Thus, to overcome these uncertainties, modeling of water resources and demands through scenario analysis is essential method for effective water resources management at catchment level.

1.2. Statement of the Problem

The social and economic transformation associated with rapid urbanization and the wide spread adoption of irrigation to overcome the climate change constraints profoundly altered the pattern of water use (Leen, 2009). Management of water resources entails approaches that needs more and better quality information about the current and potential future status of the water resources systems to be able to devise the smart decision (Leen, 2009).

There are rural and urban populations who have been deriving water from Legedara River catchment for domestic and industrial water demand, but most of the water users of the catchments are Dilla's town population (GZWMEO, 2016). However, the available water resources of the Legedara River catchment are not well understood since the catchment is ungauged and also no hydrological and water allocation modeling was done in the catchment before. Besides, Dilla town, being a center of commercial trading of the region, fast growing population, urbanization and the expansion of development and economic activities are exerting pressure on available water resources and the problem will be more severe than today.

In additionto the above troubles, inadequate information of water balance of the catchment as well as water resources management is the most important constraint towards addressing the water allocation problem of the catchment.

Thus, this research was looking to develop a clear picture through linking the water resources availability and demands to understanding the status of the existing problems in the water sector and provide a benchmark decision tools that can assist in the planning and managements of the available resources. Furthermore, this study was attempted to estimate the water balance components of the catchment in order to understand the available water resources.

1.3. Objective of the Research

1.3.1. General Objective of the Research

The general objective of this research is to Analyse thewater resources and demands of Legedara River catchment for effective water management through scenario analysis using WEAP model.

1.3.2. Specific Objectives of the Research

- To estimatethe mean monthly and annual water balance components of theLegedara River catchment (1997 - 2013).
- To estimate surfacewater resources potential anddemands of Legedara River catchment.
- To evaluate different future scenarios ofLegedara River catchment (2017-2040).

1.4. Basic Research Questions

1. What are the dominant water balance components of Legedara River catchment?
2. Can surface water resources of Legedara River catchmentfulfill existing and future water demands to the water users?
3. What will be the prospects of the nexus between water resources and demands in different management scenario?

1.5. Significance of the Research

This study will stab to model the surface water resources potential and demands for effective water management plan in different management scenarios till 2040. Thus, the result of this study is anticipated to add new insight in adopting Decision Support Tool for water management plan in urban Ethiopia for concerned stakeholders and practitioners. It will also serve as a benchmark data for system optimization, supply scheduling and further investigation of the existed problems of water supply under different scenarios.The data generated for the purposes of this research work such as, estimated water balance components, land cover/use, soil and slope map, water demands of Legedara River catchments can assists local or Regional planners to facilitate preliminarily survey.

1.6. Scope and Limitation of the Study

This study focuses on surface water resources potential and demands through scenario analysis for effective water management in Legedara River catchment. This study specifically emphases on estimation of mean monthly and annual water balance components (1997-2013), surface water resources potential,current situation water demands (2013-2016) and future scenario development (2017-2040). The study covers selected demand sites of Legedara River catchment (domestic, industrial and environmental flow requirements) for water allocation part. However, during allocation of water for environmental flow requirement, livestock water demand was considered.

The biggest challenge encountered during the study was lack of hydrological data because of the catchment is ungauged. Therefore, transferring final calibrated model parameters from gauged Waleme River catchment was used to solve the limitation of hydrological data. The study does not take in to account groundwater potential due to lack of information and data. Moreover, there is no previous research on the study area; so it was not possible to do a comparative study. The total numbers of meteorological stations in the study area are few; and the Dilla station is the only class one type and Kebado station is class three.

2. LITERATURE REVIEW

2.1. Water Resources of Ethiopia

Ethiopia possesses a substantial amount of water resources little has been developed for drinking water supply, hydropower, agriculture and other purposes. For instance, Ethiopia has 12 river basins. The total mean annual flow from all river basins is estimated to be 122BMC (MoWE, 2010). At present, surface water and meteorological data are collected and processed on a river basis through existing hydro-meteorological networks. The idea of river basins, despite its physical attributes, is more than engineering concept and encompasses the magnitude and dynamic of a resource that must be harnessed for the common good (Molle, 2006). Accordingly, it is desirable that all major river basins in Ethiopia have an integrated development master plan study, and their potential in terms of economic development. Moreover this, Ethiopia has 11 fresh and 9 saline lakes, 4 crater lakes and over 12 major swamps or wetlands. Majority of the lakes are found in the Rift Valley Basin. The total surface area of these natural and artificial lakes is about 7,500 km^2. Most of the lakes except Ziway, Tana, Langano, Abaya and Chamo have no surface outlets. Lake Shala and Abiyata have high concentrations of chemicals and Abiyata is currently exploited for production of soda ash (Seleshi*et al.*, 2007).

As compared to surface water resources, Ethiopia has lower groundwater potential. However, by many countries standard, the total exploitable groundwater potential is high (Seleshi*et al.*, 2007). According to MoWE (2010),the annual groundwater rechargeis estimated to be around 28BMC.

2.2. HydrologicalProcesses

As indicated in most hydrology literature, water can exists in gaseous, liquid and solid state. It is circulated on the planet earth mainly by solar and planetary force. Because of this circulation, various hydrologic phenomena occur in nature. This continuous chaining of hydrologic phenomena is called hydrologic cycle. Therefore, water is transported from the ocean to the atmosphere as vapor by evaporation, from the atmosphere to the land as precipitation, and back from the land to the ocean as runoff. In general, hydrologic cycle is endless, as it has no beginning or end. Consequently,hydrologic phenomena are extremely complex, and difficult both to measure and understand in full detail. In the absence of perfect knowledge, however, they may be represented in a simplified way by means of the system concept which is a set of connected parts that forms a whole (Marechel, 2004; Bogale, 2011).

2.3. Water Balance Components at Catchment Scale

A fundamental assumption in hydrology is that of the hydrological cycle being a closed system, i.e., there are no gains or losses of water from the cycle. Unfortunately, there are many occasions upon which the hydrologist has to deal with an open system that can only be described by a massbalance or water budget equation in which the difference between input (I) and output (O) is related to the change in storage (ΔS) within the time interval.

Dingman (1994) refers to a water balance as "the amount of a conservative quantity entering a control volume during a defined period minus the amount of quantity leaving the control volume during the same period equals the change in the amount of the quantity stored in the control volume during the same period time". The simple water balance equation is represented as:

$$\Delta S = I - O \quad \text{.......... (2.1)}$$

In applying equation 2.1, care must be taken in defining the so-called control volume or region over which the budget is applicable. For this study, the control volume is a catchment or drainage area bounded by its topographic divide or watershed**,** the inputs consist of precipitation (P), and possibly groundwater inflow (G_{in}), and the output comprise the discharge (Q) at the catchment outlet, transpiration from the vegetation growing within the catchment and evaporation from precipitation intercepted by the vegetal canopy and held in storage on the ground (E) and possibly groundwater outflow (G_{out}). Accordingly the changes in storage(ΔS) to be considered are principally those in the sub-surface unsaturated and saturated zones, leading to:

$$Q = P + G_{in} - Et - G_{out} \pm \Delta S \quad \text{.......... (2.2)}$$

However, to determine the water balance components of Legedara river catchment, the terms G_{in} and G_{out}arenot considered, due to absence of groundwater flow data.

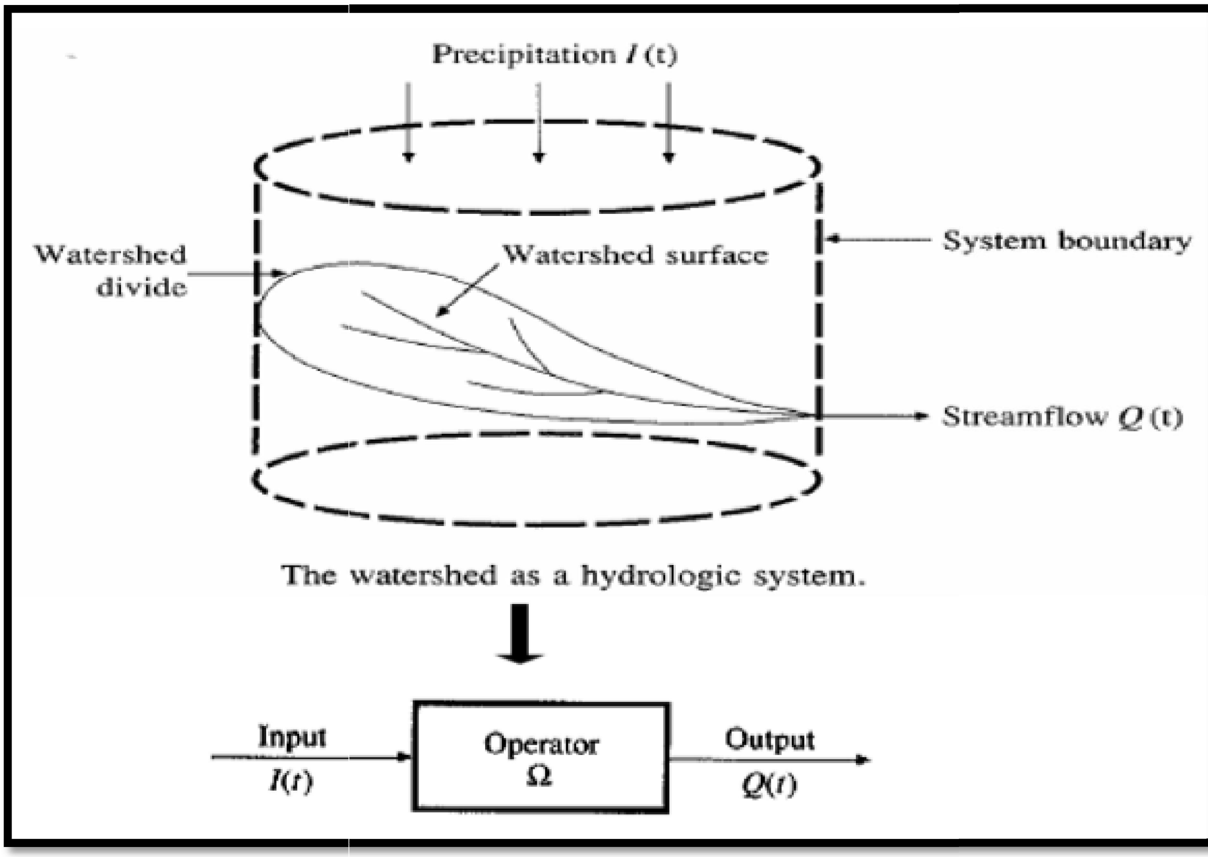

Figure 2- 1: Catchment seen as hydrological transformation operator (Dingman, 1994)

Because of these great complications, it is not possible to describe all the physical processes within the watershed with exact physical laws. Using the physical system concept the effort is instead directed to the construction of a model representing the most important processes, and their interaction within the total system. A conceptual knowledge of the physical system will still be valuable to determine the main processes, and develop a simplified but useful model. The term conceptual modeling is used for this type of analysis (Marechel, 2004).

2.4. Surface Water Potential at Catchment Scale

A catchment is the area covering all the land that contributes runoff water to a common point. It is a natural physiographic or ecological unit composed of interrelated parts and functions. Estimation of surface water can doonly at basin level (FAO, 1997). An important consideration in water resources estimation is to estimate the amount of flow is available at the outlet of river catchment. But, the problem most often encountered in water resources management studies is the need for estimating runoff from a catchment for which there is records of precipitation and no records of runoff (Bogale, 2011).Accordingly, in Ethiopia, availability of runoff records is very limited compared to rainfall records, especially for medium and small catchments. However, runoff values are necessary for such ungauged catchments for effective water resources management. As pointed out earlier in the statement of problem, the catchment is ungauged and also no hydrological modeling was done in the study area before.For this reason, it is not possible directly to quantify the amount of surface water available within the catchment.Nowadays, there are a number of approaches that are applicable to determine the potential of surface water forungauged catchments.

1. Direct estimation of parameters for ungauged catchments using theoretical applications of soil physics (Koren*et al.*, 2000).
2. Transferring calibrated gauged model parameters to ungauged catchments (Vandewiele and Elias, 1995;Kokkonen*et al.*, 2003; Mazvimavi, 2003;Marechel, 2004; Merz and Bloschl, 2004;Abeyou, 2008; Perera, 2009; Tewodros, 2012;Abebe, 2014;Visessri, 2014; among others).
3. Transferring stream flow of gauged catchment to ungauged catchments using runoff coefficient method as suggested by Jamshid(2003);Kebede(2010), while the most common approaches are transferring calibratedgauged model parameters to ungaugedcatchments (Kokkonen*et al.*, 2003; Merz and Bloschl, 2004; Marechal, 2004; Abeyou, 2008; Perera, 2009;Bogale, 2011; Visessri, 2014; among others).

2.5. Ungauged Catchments

The catchments with inadequate stream flow data are classified as ungauged (Marechel, 2004). Nonetheless, a number of methods have been attempted to estimate the runoff forungauged catchments during the past four decades. A summary of selected previous studies shows that regionalization of model parameters was the most common approach. This approach seems effective in estimating the model parameters of ungauged catchment with limited sources (Kokkonen*et al*., 2003;Abeyou, 2008; perera, 2009). Several new methods were also attempted to regionalize model parameters includes application of spatial proximity (Merz and Bloschl, 2004). It is understood that from the previous studies the accuracy of estimation of runoff from ungauged catchment cannot be granted by a particular method, but that depends on the data availability (Kim and Kalurachchi, 2008).

List of some previous studies on ungauged catchments in Ethiopia:

Perera (2009) modeled ungauged catchment hydrology as case study of Lake Tana Basin. The objective was to apply a hydrological model and regionalization to simulate runoff from gauged and ungauged catchments. The researcher concluded that transferring calibrated model parameters from gauged to ungauged catchment is a popular method to estimate ungauged catchment runoff.

Abeyou (2008) 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 catchment by Rainfall-Runoff modeling. Daily flows from ungauged catchments are estimated by transferring model parameters from gauged catchments using a regionalization procedure, spatial proximity procedure and catchment area ratio method. All procedures were aimed to transfer information from gauged to ungauged catchment. The author concluded that such kinds of procedures are a good method for estimation of runoff of ungauged catchments.

Abebe (2014) assessed surface runoff potential and irrigation suitability assessment of An-Lemo river watershed in Hadiya Zone. The main goal of research work was to assess the surface runoff potential and irrigation suitability of An-Lemo river watershed using SWAT model. The author estimated that the runoff of the catchment by transferring calibrated model parameters from gauged Gudar to ungauged An-Lemo catchment. But, before transferring the calibrated model parameters, the author studied the similarity of the two catchments based on catchment and climate characteristics, spatial proximity and data availability. The author concluded that the two catchments are similar in hydro-meteorologically and it is possible to estimate ungauged runoff of An-Lemo watershed.

Tewodros (2012) developed physical based Rainfall-Runoff modeling in the northern Ethiopia highlands the case of Mizewa watershed. The objective was to investigate the hydrology of Mizewa river catchment using SWAT model. The researcher estimated surface runoff ofMizewa watershed; after calibration and validation of the SWAT model with observed river flows of gauged Gummera watershed as Mizewaungauged watershed was found to be hydro-meteorologically similar to Gummera gauged river watershed.

Bogale (2011) studied on predicting discharge at ungauged catchment using Rainfall-Runoff model: case study on Omo-Gibe river basin. The general objective of the study was to apply a hydrological model and regionalization technique and simulate runoff for ungauged catchments of Omo-Gibe river basin. Based on the availability of the data, the author selected six physical catchment characteristics for the purpose of transferring information from gauged to ungauged catchments. These are catchment area, longest flow path, mean elevation, mean annual rainfall, average catchment slope and circularity ratio. Based on these criteria the author selected representative catchment in order to transfer calibrated model parameters from gauged to ungauged catchments. The author reported that during the selection of representative catchments, among the available 22 sub-catchments that are considered for the purpose of rainfall-runoff modeling, 16 sub-catchments fulfilled the set criteria but 6 sub-catchments failed. The failure of some of the sub catchments is expected to be due to quality of hydro-metrological and Physiography and geography difference.

2.6. Overview of Water DemandAssessment

The demand of water is determined by social, economic and environmental needs (number of households, area of irrigated land and crop types, minimum stream flow, etc.) and the water use rate of each activity. In the context of public water supply, water demand is the total volume of water necessary orneeded to supply customers within a certain period of time. water demand is the algebraic sum ofthe quantity of water utilized by consumer (consumption) and the amount of water physicallylost from the system (leakage) which is expressed as per capita demand (Trifunovic, 2006). Accordingly, per capita water usage varies widely dueto the differences in climatic conditions, standard of living, population growth, type ofcommercial and industrial activities and water pricing.

Of the factors that determine development potential in a given geographic area, the availability of water for residential, commercial, and industrial and environmental purposes is a primary indication of prospective growth. Governmental bodies at the regional, state and federal levels often need to identify water supply availability in order to identify growth potential (Mugatsia, 2010; Abdullahi, 2015).

According to Arranz (2006), the demand for water resources of sufficient quantity and quality for human consumption, sanitation, agriculture, and industrial uses will continue to intensify as the population increases and global urbanization, industrialization, and commercial development accelerate.Therefore, Computer based Decision Support Systems (DDS) are being used worldwide in order to manage more wisely our water resources. A Decision Support System allows decision-makers to combine personal judgment with computer output, in a user- machine interface, to produce meaningful information for support in a decision making process. Such systems are capable of assisting in solution of all problems (structured, semi structured, and unstructured) using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of the decision maker's approach to problem identification and solution. A DSS must help decision makers at the upper levels, must be flexible and respond to questions quickly, must provide for "what if" scenarios and must consider the specific requirements of the decision makers. Additional important characteristics are accessibility, flexibility, facilitation, learning, interaction and ease of use (Arranz, 2006).

If assessing water demand in a given catchment is essential as discussed above; what available models are there which are capable of modeling water demand and which is best suited to model water demand in the study area is a crucial question any one can ask.Of course there are various models which are capable of modeling water demand in a given catchment or basin.However, WEAP model was selected as the best suitable to model the water demand as well as the water resources of Legedara River catchment.

2.7. Integrated Water Resources Management

IWRM "is a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000).This definition adopted by the global water partnership initiative applies in to two major areas of concern:

1. The natural system with its critical importance for resources quality and availability
2. The humans system, which fundamentally determine the resources use, pollution, and which must also set the development priorities.

This definition captures a holistic view of IWRM; however critics view it as highly hypothetical, dismissing it as an amorphous definition. This is seen as having problems in concept and implementation, especially for micro and macro-scale projects (Biswas, 2004).

2.8. Hydrology and Water Resources Management Models

Models are increasingly becoming indispensable tools for planning, design and management of hydrological base infrastructure. It is used extensively and plays an important role in fulfilling the care tasks of water management, in policy preparation and research (Shumet and Mengistu, 2016). The concept of model is a very broad one; it is distinguished on the basis of the reason for application, varying from policy arrangement to scientific research. A model is systems methodology approach and helps to define and evaluate numerous alternatives that represent various possible compromises among the conflict groups, values and management objectives (Yates *et al.,* 2005).

There are several models that are designed to simulate water development and management policies in river basins. Each of these models is based on a node-link network representation of the water resource system being simulated. All contain menu-driven graphicsbased interfaces that facilitate user interaction (Mugatsia, 2010). These models are appropriate for use in shared vision exercises involving stakeholder involvement in model building and simulations. Some of these models include: River Basin Simulation Model (RIBASIM), Water Balance Model (WBalMo), MULti-Sectoral Integrated and Operational Decision Support System (MULINO–DSS), Simplified Water Allocation Model (SWAM) and Water Evaluation and Planning System (WEAP).

Water resources planning and management was generally an exercise-based on engineering considerations in the past. Nowadays, it increasingly occurs as a part of complex, multi disciplinary analysis that brings together a wide range of individuals and organizations with different interests, technical skills, and options.Successful planning and management of water resources requires application of effective integrated water resources management models that can solve the encountering complex problems in these multi-disciplinary investigations. Water resource planning and management processes aided IWRM models have become more common, however generic tools that can be applied to different basin settings are frequently difficult to use because of the complex operating rules that govern individual water resource systems.IWRM models, which can incorporate and operate hydrology and management processes at the same time, are needed to help planners under different reality cases and management options. These IWRM models must be effective, useful, easy-to-use, and adaptive to planners' priorities (Yates *et al.*, 2005).

Effective IWRM models must deal with the biophysical system, which create runoffgeneration and its movement, and the socio-economic management system, which create waterstorage, allocation, and delivery (Yates *et al.*, 2005;Mugatsia, 2010). For the biophysical system, the hydrology model that simulates the physical processes must be used, and for the socio-economic system, planning model that relates the management system for the operation of water structuressuch as reservoirs and channels and the allocation of water must be considered (Yates *et al.*, 2005)(see in Figure2.2).

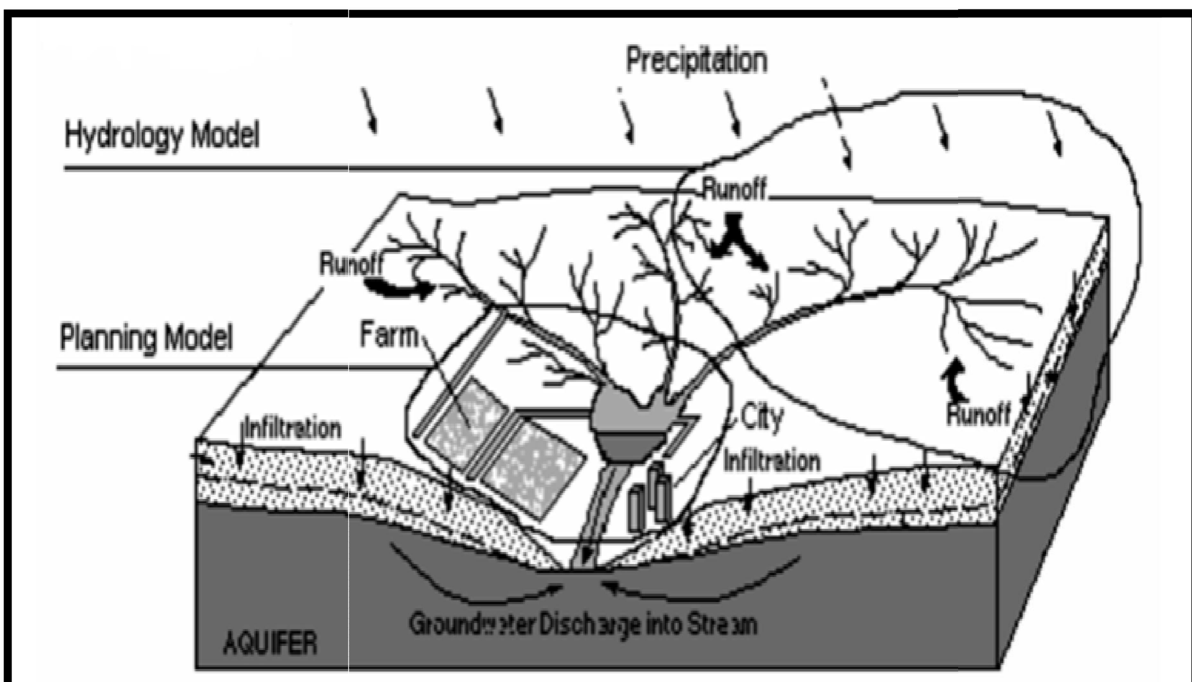

Figure 2- 2: Implications of water resource infrastructure on the hydrologic cycle (Yates *et al.*, 2005)

2.8.1. Selection of the Model

To select the appropriate models for solving specific problems, the classification of models depending on the spatial scale and physical detail of the model are important to know the determination of model behavior as required data, required expertise, expected accuracy and user-friendliness. However, some models are better in spatial water quality analysis, supply and demand management in the catchment, whereas others are good analysis of project for river and reservoir routing.

For present study, WEAP 16.01 was applied in order to simulate water resources and demands for effective water resources management. The model was preferred to others because of its robustness and ease of use depending on data availability. The model can perform both lumped to distributed catchment hydrological simulation and can handle aggregated to disaggregated water demands of various sectors (Yates *et al.*, 2005; Mugatsia, 2010; Singh *et al.*, (2014 and 2016); Abdullahi, 2015; SEI, 2016; Shumet and Mengistu, 2016).Accordingly, WEAP integrate hydrologic sub-modules such as a conceptual Rainfall-Runoff model, groundwater model and a water quality model.The system is therefore appropriate for studying catchments with minimum to moderate data availability.WEAP is a new generation of water planning and management software, and the powerful capability of today's personal computers can easily use it everywhere to access to theappropriate tools. The model was selected for the purpose of this study.

2.8.2. Water Evaluation and Planning (WEAP) Model

The Water Evaluation and Planning (WEAP) model was developed by the Stockholm Environment Institute-Boston, Tellus Institute, U.S.A since 1990. It is an integrated Decision SupportSystem (DSS) designed to support water planning that balances water supplies and multiple waterdemands. WEAP incorporates issues such as allocation of limited water, environmental qualityand policies for sustainable water use, unlike the conventional supply oriented simulation models.It gives a practical integrated approach to water resources development incorporating aspects ofdemand, water quality and ecosystem preservation (SEI, 2016).WEAP is a river basin simulation model with geo-spatial capabilities that is capable of simulating the allocation of water throughout a river basin based upon a user specified time step. As a database, WEAP provides a system for maintaining water demands and supply information. As a forecasting tool, WEAP simulates water demand, supply, flows, storages, pollution generations, and discharge.As a policyanalysis tool, WEAP evaluates a full range of water development and management options, andtakes account of multiple and competing uses of water systems (SEI, 2016).

WEAP can address a wide range of issues, e.g., sectoral demand analyses, water conservation,water rights and allocation priorities, groundwater and stream flow simulations, reservoiroperations, hydropower generation, pollution tracking, ecosystem requirements, vulnerabilityassessments, and project benefit-cost analyses.One of the strengths of WEAP is that it is adaptable to whatever data is available to describe awater resources system. That is, it can use daily, weekly, monthly, or annual time-steps tocharacterize the system's water supplies and demands. This flexibility means that it can beapplied across a range of spatial and temporal scales. Indeed, WEAP has been used throughoutthe world to analyze a diverse set of water management issues for small communities and largemanaged watersheds alike. WEAP operates always in an optimization water allocation model,based on priorities set for each demand site. This makes WEAP unique in comparison to otherwater allocation tools (SEI, 2016).

WEAP applications generally include several steps. The study definition setup the time frame,spatial boundary, system components and configuration of the problem. The current accountsprovide a snapshot of actual water demand, pollution loads, resources and supplies for thesystem. Alternative sets of future assumptions are based on policies, costs, technologicaldevelopment and other factors that affect demand, pollution, supply and hydrology. Scenarios areconstructed in such a way that it consisting of alternative sets of assumptions or policies. Finally, the scenarios areevaluated with regard to water sufficiency, costs and benefits, compatibility with environmentaltargets, and sensitivity to uncertain in key variables.

WEAP model simulates water system operations within a river system with basic principles of water accounting on a user-defined time step, usually a month. Simulation allows the prediction and evaluation of “what if” scenarios and water policies such as water conservation programs, demand projections, hydrologic changes, new infrastructure and changes in allocations or operation.

Scenario development and analysis are a powerful way to evaluate the outcomes and consequences of different patterns of resource use and management practices. By understanding these outcomes and consequences these can be enormously useful in decision making. WEAP is very effective tool to handling scenario analysis. It is all the more important, then, to take pains when developing the scenarios to be analyzed.

To sum up, WEAP is one of the useful IWRM models, and capabilities to build complex, demand models for municipal, industrial, agricultural and environmental demands of different spatial and temporal scales (Yates *et al.*, 2005).Nowadays, WEAP has been used throughout the world to analyze the water management issues in small scales to large ones.

2.9. Previous Studies Using WEAP Model

The first version of the model was developed in 1990. Since then, it has been applied in a lot of researchwork conducted in quite a number of basins in different countries in worldwide. The first major application of WEAP was to study on the water development strategies and water supply- demand analysis for the Aral Sea region in 1990 with the sponsorship of SEI (Raskin*et al.*, 1992).The version of WEAP at that time had several limitations such as allocation scheme, demand site priorities (Raskin*et al.*, 1992). Because of these deficiencies, WEAP introduced major advancement including a modern Graphic user interface and a robust solution algorithm to solve the water allocation problem. Moreover, WEAP integrate hydrologic sub-modules such as a conceptual rainfall-runoff model, groundwater model and a water quality model (Yates *et al.*, 2005).

WEAP has been used in several water related researches/ projects across the world. For example, Shumet and Mengistu (2016) assessed the Impact of existing and future water demand on economic and environmental aspects (case study from Rift Valley Lake Basin: Meki-Ziway Sub Basin), Ethiopia. The authors simulate the catchment runoff of Meki-Ziway Sub Basin using Rainfall-Runoff (Simplified Coefficient) method by WEAP model. After knowing the available water of the Sub Basin, the authors allocatesto the selected demand sites in order to know the impacts of water demand on economic and environmental aspects.WEAP was used to determine the likely impact of a number of possible development scenarios in Lake Tana Catchment, Ethiopia, on lake water levels (Alemayehu*et al*., 2010). It was also used to evaluate Ethiopia's policy of large dam construction in the Blue Nile River basin by simulating the impact of one downscaled midrange climate change scenario on the performance of existing and planned hydropower and irrigation schemes (McCartney and Girma, 2012).

WEAP is widely used in other parts of the world, too. For example, Singh *et al.,* (2014) developed hydrological modeling of Mahanadia river basin using FAO-Rainfall-Runoff (Simplified Coefficient) model by WEAP model. Arranz and McCartney (2007) applied WEAP Model to assess future water demands and resources in the Olifants Catchment, South Africa. Mounir*et al*. (2011) also conducted a study using WEAP model to investigate scenarios of future water resource development in the Niger River Basin in Niger Republic. Similarly, it was used to assess the potential effects of climate change and adaptive management on irrigation water supply in the Cache Creek watershed in California (Mehta *et al.,*2013).

2.10. Rainfall-Runoff Modeling

Rainfall-Runoff modeling is very significant in catchment management. Simulation of catchment hydrology gives an indicator of resources capacity. For the purpose of water resources assessment, it is necessary to have understanding of catchment flow condition. A rainfall-runoff model is a simplified representation of real world hydrological process.WEAP 16.01 introduces major advances including a modern graphic user interface, a robust solution algorithm to solve the water allocation problem, the integration of hydrological sub modules that include a conceptual rainfall-runoff model, groundwater model and a water quality model (Yates*et al.*, 2005; Mugatsia, 2010; Singh*et al.,*(2014 and 2016);SEI, 2016; Shumet and Mengistu, 2016).There is a choice among two methods to simulate catchment runoff using WEAP model. The choice of model structure usually depend on a number of factors including, the catchment properties, prior knowledge of the catchment hydrology process, data availability, the modeling tasks, the modeler's expertise and experience and preference of decision makers (Marechel, 2004).

1. FAO-Rainfall-Runoff (Simplified Coefficient) Model

The FAO-Rainfall-Runoff method determines evapotranspiration for catchments using crop coefficients. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links(Mugatsia, 2010; Singh *et al.,*(2014 and 2016); Abdullahi, 2015; SEI, 2016; Shumet and Mengistu, 2016).

2. Soil Moisture Model

The Soil Moisture Model is the most complex methods, representing the catchment with two soil layers, as well as the potential for snow accumulation. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non agricultural land, runoff and shallow interflow, and changes in soil moisture. This method allows for the characterization of land use and/or soil type impacts to these processes. Base flow routing to the river and soil moisture changes are simulated in the lower soil layer. Correspondingly, the Soil Moisture Method requires more extensive soil and climate parameterization to simulate these processes. These kinds of data arenot available in the study catchment.

Thereforefor this particular study, FAO-Rainfall-Runoff method was used for deriving model parameters of gauged catchment as well as for estimating ungaugedcatchment runoff.

2.11. Scenario Development

In a way more relevant to water resources, scenarios are defined as alternative sets of assumptions such as different operating policies, costs, and factors that affect demand such as demand management strategies, alternative supply sources and hydrologic assumptions, with changes in these data able to grow or decline at varying rates over the planning horizon of the study. Thus, scenarios are not created from the minds of the requirements engineers; their definition should be anchored on real situations (Leite*et al.*, 2000, cited by Tena*et al.*, 2016). Accordingly, the typical characteristic of scenario analysis method is that it can model many real problems where decisions are based on uncertain information presented as a set of possible outcomes (i.e., scenarios). The most important aspects of applying models is to exploring indirect impact external driven scenarios, such as population growth, climate change, and direct impact management scenarios by water management and policy makers, such as changes in reservoir operation, water allocation and irrigation practices (SEI, 2016).

Scenarios can address a broad range of questions. An important concept of WEAP is thedistinction between a reference or "business as usual" scenario and alternative policy scenarios. The "business-as-usual" scenario incorporates currently identifiable trendsin economic and demographic development, water supply availability, water-use efficiency andother aspects. No new water conservation measures or supply projects are included in the"business-as-usual scenario. This scenario provides a reference against which the effects ofalternative policy scenarios may be assessed (SEI, 2016).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The study was conducted in Legedara River catchment, SNNPR, Ethiopia.The Legedara River catchment lies in an area between 6°22′and 6°27′Nlatitude 38°17′and 38°28′Elongitude. It is a tributary stream of Gidabo River. The river Legedara is draining through an area of 94.87km^{2}from its source up to its confluence with the outlet. Out of the total catchment area, about 59.5km^2 area lies in Sidama Zone and remaining 35.37km^2 of an area lies in Gedeo Zone.It is located at 359km south of AddisAbaba and 90km from capital of the regional state, Hawassa. The location map of Legedara River catchment is shown in Figure 1.

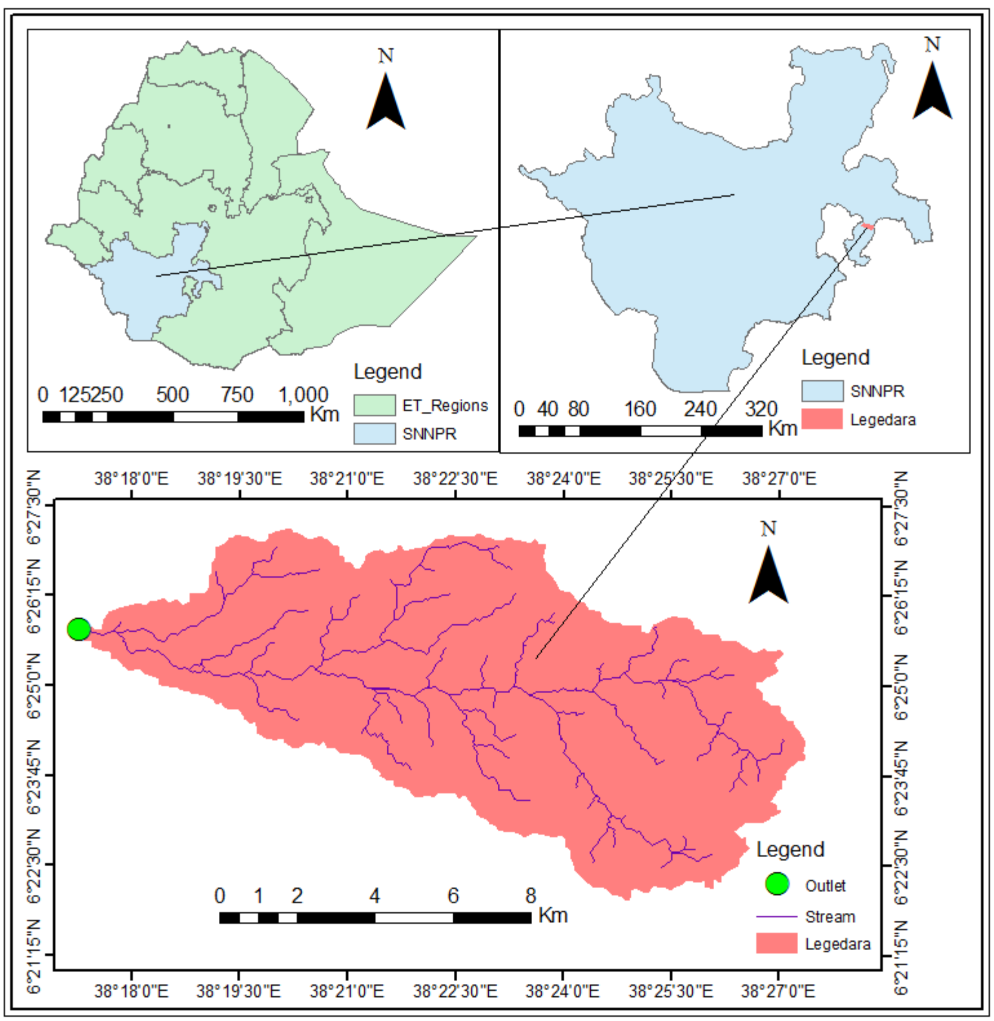

Figure 3- 1: Map of the study area

3.1.2. Climate

The climate of Ethiopia is mainly controlled by the seasonal migration of the Inter-tropical Convergence Zone (ITCZ), which is conditioned by the convergence of trade winds of the northern and southern hemisphere and the associated atmospheric circulation. It is also highly influenced, regionally and locally, by complex topography of the country. The easterly and southeasterly moist air currents ascend over the highlands in spring, produce the main rainy season in southeastern Ethiopia in general, and bring “high rains” of spring (March to May) to most parts of the country (Tilahun, 2015). Legedara catchment, therefore, gets its first maxima rainfall during spring and receives the year’s secondary maxima rainfall during autumn from the Indian Ocean easterlies while the catchment receives small rainfall in summer compared to spring (April to May)and autumn (September to November) due to the case that the Southerly Indian Ocean air currents lie in the lee side of the highlands in summer and Atlantic westerlies reach the southeastern lowlands after losing their moisture on the highlands to west.

Thus, LegedaraRiver catchment experiences a humid type of climate, which is characterized by abundant moisture and relatively high temperature. The rainfall pattern is bimodal which divided the year in to two main seasons. The bimodal type of rainfall pattern is characterized by a double peak rainfall pattern. It receives an annual rainfall of 1316.42 mm. The annual maximum and minimum temperature of the catchment area is about 27.8^{0}C and 11.7^{0}C respectively. The average wind speed is 0.62 m/s.

3.1.3. Demography of the Study Area

There are rural and urban population lives in Legedara River catchment.According to the 2013 census report of the Ethiopian Central Statistical Agency (CSA), the total projected population of Dilla town was reported as101957, 106985, 112874 and 119276 for the year of 2013, 2014, 2015 and 2016 respectively.According to the report of DillaZuriya and DaraWereda, thetotal number of rural populationliving in the catchment isestimated at97856.

3.1.4. Topography

There is high elevation change between the upper and downstream of the catchment which is 2999m.a.s.l and 1427m.a.s.l of the upstream and downstream edge of the catchment respectively. The altitude decreases from east to west in the catchment. The topography of

Legedara River catchment at the eastern part characterized by high mountains 2999m.a.s.l with steep slope. The lower catchment lies at 1427m.a.s.l at the outlet of the river (see Appendix Figure 7.10).

3.1.5. Soil

There are three major soil groups in Legedara River catchments: Cambisols, Nitosols and Vertisols of which again classified in to four soil units: Eutriccambisols, Eutricnitosols, and Chromicvertisols and Dystricnitosols. The Eutriccambisols is found in the upper and middle part of the catchment. Dystricnitosols is found in the upper part of edge while chromic vertisols and eutricnitosols are found at the downstream part of the catchment (seeFigure 4.3).

3.1.6. Land cover/ use

The upper parts of the catchment area are agricultural land; the middle parts of the catchment are agro-forestry and built up and the lower part are shrub and bare land(see Figure 4.2).The agricultural land cover commonly consists of legume, bean, wheat, inset, vegetables, fruit, coffee, maize and sugarcane. Agro forestry land consists of forest mixed with coffee, banana, ananasand inset. Built up land consists of urban areas such as Dilla town, and other small kebeles such as gola, adida, shigeto, oticho, hytile and fulanto. The other portion of the catchment covers by shrub land and bare land.

3.1.7. Slope

Catchment slope reflects the rate of change of elevation with respect to distance along the principal flow path. Most part of the lowland of catchment lies between 0-20%, middle 21-43% and the upper land is above 44% (see Figure 4.4).

3.1.8. Hydrogeology

LegedaraRiver catchmentis situated at the foot of an over 2999m high mountain which coincides with the eastern fault belt of the Rift Valley. Both shallow and deep ground water is available in the catchment. The shallow groundwater occurs in the reddish brown soil of the weathered trachyte whose thickness is about 6m.Deep groundwater occurs in the underlyingvolcanic rocks mainly within fractures and weathered zones layers of sandy deposits betweendifferent lava flows (GZWMEO, 2016).

3.1.9. Drainage Systems

LegedaraRiver catchmentis surrounded with three perennial rivers from three directions namely Legedara, Walame and Chichu. Both Walame and LegedaraRiver linked after a short distance from Dilla town and flow in to Lake Abaya.The origin of Legedara River that flow towards the catchment start from the Buna-KobaMountain specifically Fulano and HytileKebeles.

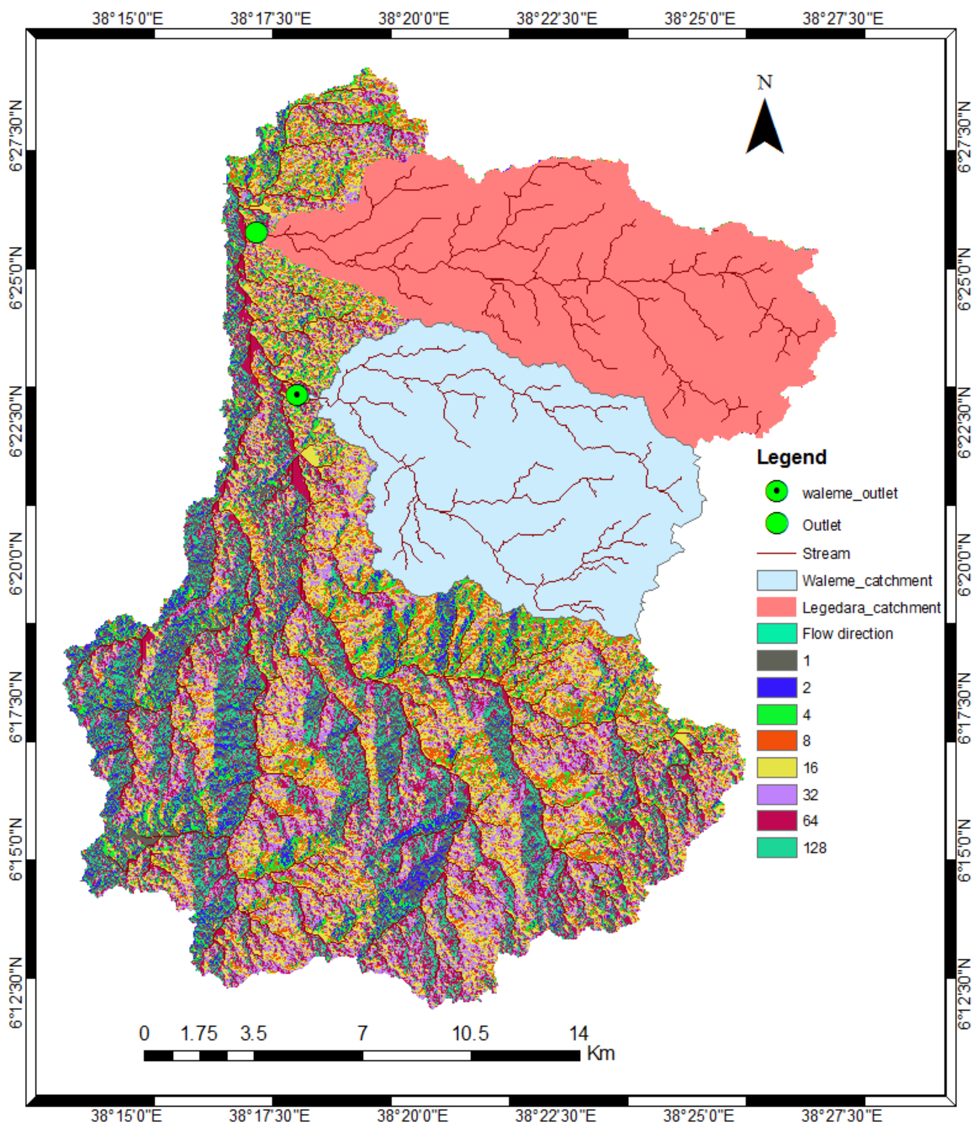

Figure 3- 2: Drainage systems inside and outside of the catchment

3.2. Materials

To effectively execute the research, the following materials, data and softwarewere used:

GPS and Digital Camera: GPS and Digital Camera were used to collect geographic coordinate values and field photographs, respectively. The geographic coordinate values were used as ground truth points to locate field photographs on satellite images for supervised classification and to identify outlet of catchment.

Topographic Map: Topographic map of the study area was used as a background for GPS to locate the samples of ground truth data.

ArcGIS: To obtain physical properties and spatial information of the catchment

DEM data: It is used as input data for ArcGIS software

Meteorological and Hydrological data: It consists of rainfall, temperature, relative humidity, wind speed, sunshine hour and stream flow.

WEAP model: It is used to simulate water resources and demands of the catchment

ERDAS IMAGINE: It is used to classify land cover map of the catchments

Microsoft Excel spreadsheet: To calculate statistical parameters.

Soil data: It is used to classify the soil units of the catchments

3.3. Methodology

This section describes the methods which were used in this research. It focuses on the hydrological analysis and water management simulation in the WEAP16.01 system.

3.3.1. General Framework of the Study

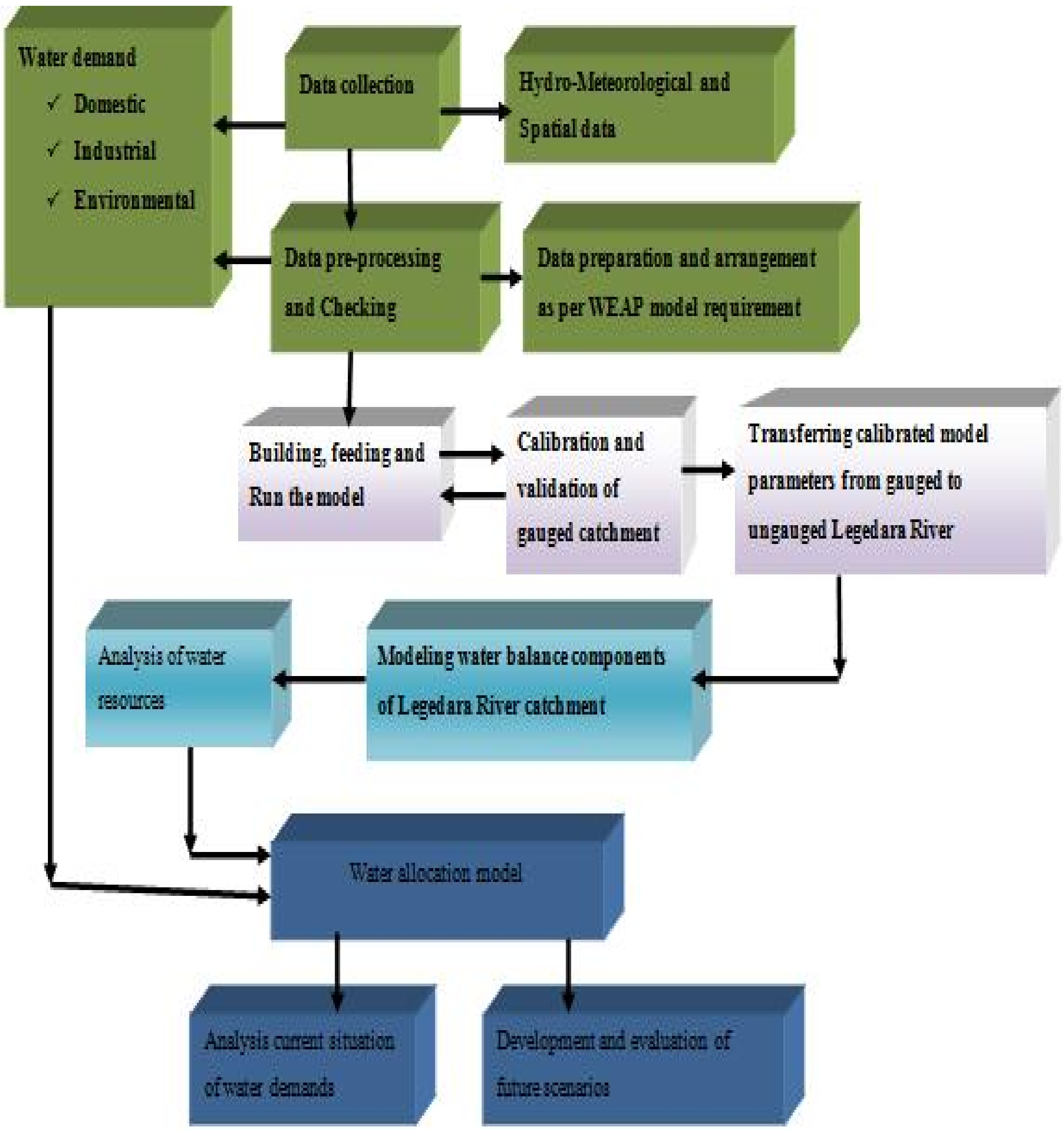

Figure 3- 3: Research design or flow chart

3.3.2. Methods of Data Collection

In order to achieve the objectives of the research, both primary and secondary data were used as input parameter for the model.The major data types that were used in this study are meteorological data, hydrological data, soil type, land use, water demand data, and GIS vector maps of catchments.

Meteorological and hydrological data were obtained from National Meteorological Services Agency and Ministry of Water, Irrigation and Electricity of Ethiopia respectively.

Two meteorological stations found in and around the Legedara river catchment. Dilla stations is the only synoptic type in this catchment, thus all necessary weather parameters required are from this stations. In Kebado station only rainfall,minimum and maximum temperature measurement values available.

Table 3- 1 : Location of meteorological stations

Station Name	Location		
	X (longitude)	Y (latitude)	Elevationm.a.s.l
Kebado	38°20’43.5’’	6 °26’00.6’’	1707
Dilla	38°18’24.9’’	6 °22’49.5’’	1615

Soil data FAO map of East Africa, were obtained from Ministry of Water, Irrigation and Electricity of Ethiopia, GIS Department.

Digital Elevation Model (DEM) define the topography of the area by describing the elevation at any point at a given location and specific spatial resolution as a digital file. Drainage pattern, slope, channel width and stream length within the catchment were prepared using DEM. The raw DEM were downloaded from United States Geological Survey (USGS) with 30m×30m resolution and processed using ArcGIS 10.1 software package.

Analysingthe land use data of the catchment,is necessary in order to represent the behavior of hydrological process of the catchment. Therefore, the landsatimegeof the catchment wascollected from Ethiopian Mapping Agency Service and field observation. GPS locations of the main land cover types on the catchment were collected to support the supervised image classification.

The lack of information on water resources was a major challenge in the catchment. Due to the lack of sufficient hydrological data such as river flow of Legedara catchment, it was not possible to use recorded flow data in this model.Therefore, the runoff was generated by means of transferring calibrated model parameters from gauged catchment.So, the gauged catchment of stream flow data was obtained from Ministry of Water, Irrigation and Electricity of Ethiopia, Hydrology Department.

In order to model the current and future water demands among multiple water users, current information and future projections are necessary; therefore in this study total population with annual population growth rate was gathered from Ethiopian Central Statistical Agency (CSA).

The demand sites and their corresponding annual activity level of the study area were identified from Dilla Town Water Supply and Sewerage Office.

Other required data, were obtained from the relevant published and unpublished documents including census and survey reports, journals, books and internet websites.

3.3.3. Data Pre-processing and Checking

The collected data can contain errors due to failures of measuring device or recorder. So, before using the data for specific purpose, the data have to be checked and errors have to be removed. The analysis was extended to hydrological and meteorological data to prepare input data for water resources and demand estimation using WEAP model.

i. Rainfall data

Rainfall data sets of two rain gauge stations namely Kebado and Dilla are obtained from National Meteorological Agency of Ethiopia.Hence, for the computation of areal depth of rainfall Kebado and Dilla data sets wereconsidered.Sometimes the rainfall amounts at certain rain gauge stations for a certain days may be missed due to the absence of some observer or instrumental failure. In such cases, it may be needed to estimate the missing rainfall amount by approximating the value from the data of nearby station. Missing records of the rainfall stations were estimated by using station year method which is recommended to estimate missing data in regions when annual rainfall among stations differ by less than 10 % (Dingman, 2002).

To prepare rainfall data for further application, their consistency was checked using double mass curve analysis. A plot of accumulated rainfall data at site of interest against the accumulated average of the surrounding station is generally used to check consistency of rainfall data and the result shows no significant shift of slope on plot isfound (see Appendix Figure 7.1 and 7.2).

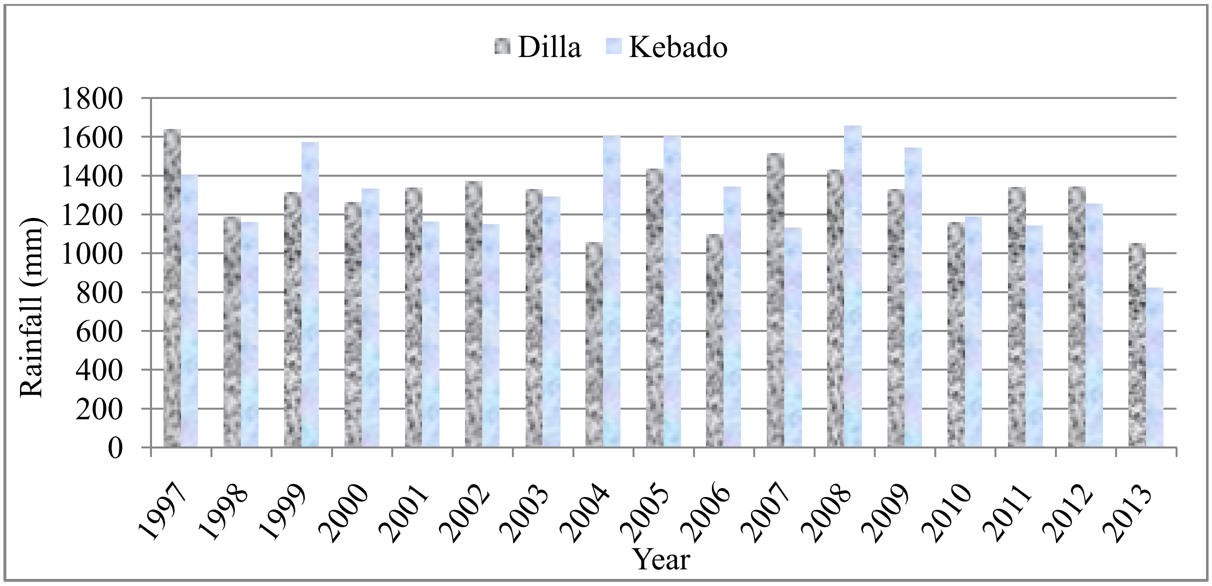

Figure 3- 4: Annual rainfall distribution of the station

ii. Stream flow data

Stream flow data of Waleme river catchment at sala, near Dilla University was used for calibration and validation of the model. The data covers the year from 1997 – 2013 (see Appendix Table, 7.3).

Internally, WEAP uses a value of -9999 to represent missing values when reading from a file, and does not include them on charts or tables.Many WEAP calculations will not accept missing value and will cause an error.For example, if the climate and stream flow data has gaps, the gaps must fill in order to use the data for catchment calculations.The gaps can be filled by one of the ReadFromFile methods (Interpolate, Repeat, and Replace) (SEI, 2016). Therefore for present study, the missed values of stream flow data was filled using interpolation technique by WEAP model.

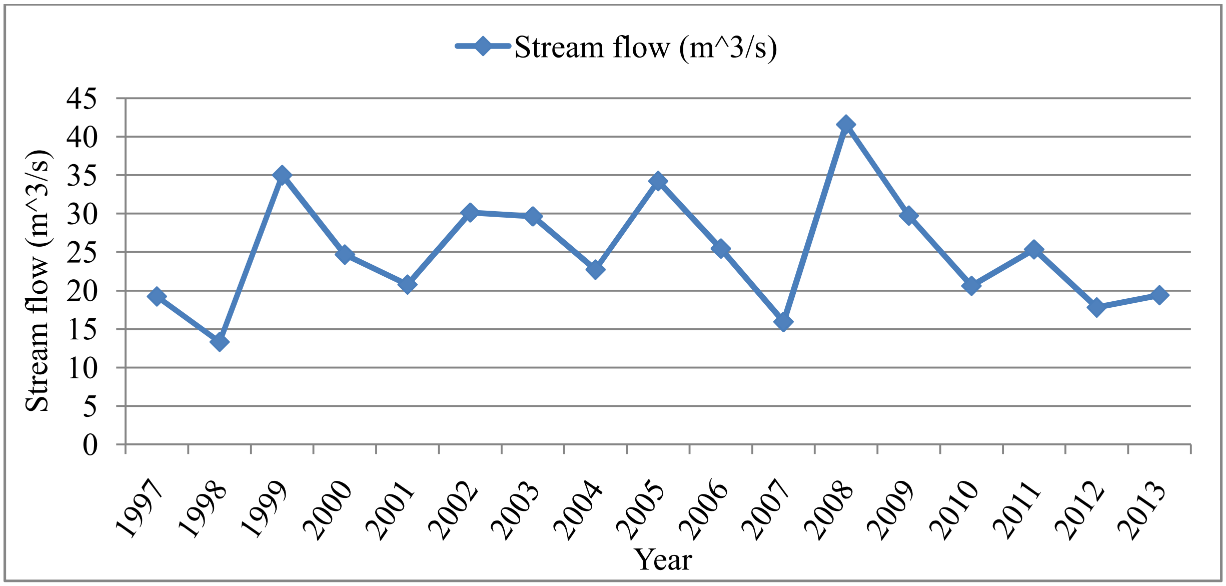

Figure 3- 5: Annual stream flow data of Waleme river catchment

Other meteorological data such as wind speed, relative humidity,minimum and maximum temperature and sunshine hours were collected for the purpose of reference evapotranspiration calculation and the collected data had a missed records ranging from one month to five month in some case. Therefore, an average value of the precedent month to the same month to the missing data has been filled.

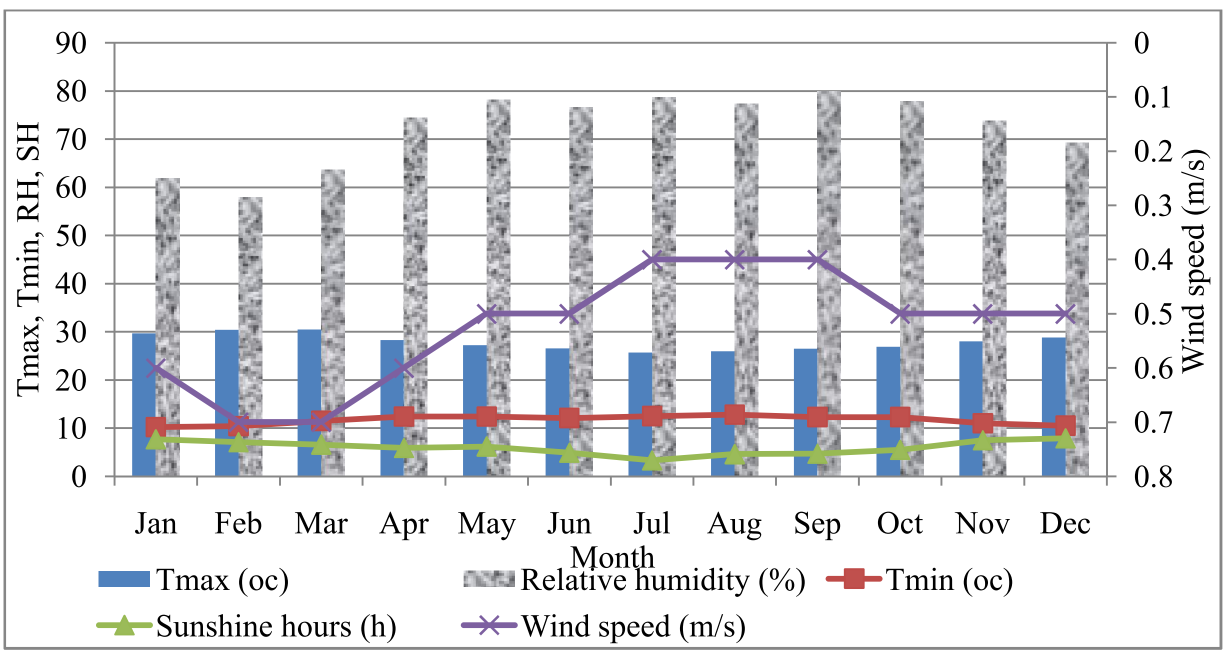

Figure 3- 6: Mean monthly climatic data

3.3.4. Parameter Derivation

As described in section 1.2, Legedara River catchment is ungauged. As a result, in this study calibrated model parameters of gauged catchments are transferred to ungauged catchments to estimate catchment runoff and water balance components. Parameters are transferred based on spatial proximity, catchment characteristics such as land cover/use, soil type, slope and climate and others are data availability (see section 2.4 and 2.5). Parameters transferred based on physical catchment characteristics referred to as regionalization is a technique that relates hydrological phenomenon to physical and climate characteristics of a catchment (Young, 2005). The approach has five distinct steps that are subsequently described in the following sections.

1. **Selection of representative catchment and catchment characteristics**

The choice of catchment from which parameters to be transferred is usually based on some sort of similarity measures. One common similarity measure is spatial proximity, based on the rational the catchment that are close to each other will have similar runoff regime as climate and catchment conditions will only vary smoothly in space (Merz and Bloschl, 2004). Other similarity measure are the use of climate and catchment attributes such as land use, soil type and topographic characteristics and other most important consideration is data availability.

In this study, spatial proximity, climate and physical catchment characteristicswere used to select representative catchment in order to transfer information from gauged to ungauged catchment.

A. Land cover

The characteristic of land cover is one of the most used physical catchment characteristics when establishment of relationship between gauged and ungauged catchment. Satellite images of the catchments had been purchased from Ethiopian mapping Agency and used for land cover classification. LANDSAT images of 2013 were used and the general information about the images is: Path/Row: 168/56, Acquisition date: 07-Jan-2013, Data set: ETM+, Resolution: 30m×30m and the images were analyzed using ERDAS IMAGIN 14.0 software.The land cover map, which has been evaluated based on field data.

B. Soil

The soil map of the major soil groups of the catchments classified as per the FAO soil group was used. This map was collected from GIS Department, Ministry of Water, Irrigation and Electricity of Ethiopia.

C. Climate

The most commonly used characteristics is the mean annual rainfall and monthly rainfall of wet, intermediate and dry season in order to select representative catchment and also other climate parameters such as wind speed, relative humidity, temperature, sunshine hours were considered

D. Geography and Physiography

Average elevation: Average elevation is one of the parameters used for physical catchment characteristicsand is obtained as an output in the delineation of catchment using ArcGIS 10.1 software package (see Appendix Figure 7.10)

$$AE = \frac{H\max + H\min}{2} \qquad (3.1)$$

Where: AE: Average Elevation of the catchment m.a.s.l (m),Hmax : Maximum altitude of the catchment m.a.s.l (m), Hmin: Minimum altitude of the catchment m.a.s.l(m)

Hypsometric integral: this indicates the distribution of elevation across the catchments and evaluated as:

$$HI = \frac{AE - H\min}{H\max - H\min} \qquad (3.2)$$

Where: AE: average elevation of the catchment m.a.s.l(m), Hmax: Maximum elevation of the catchment m.a.s.l(m), Hmin: Minimum elevation of the catchment m.a.s.l(m)

Average slope:Slope is one dominant factor that controls the water flow velocity where a high slope result in high velocities that reduce the travel time of water to reach the catchment outlet (Mazvimavi, 2003). A percentage of slope mapof the catchmentswere calculated using ArcGIS 10.1.

Catchment shape: Basin shape is not usually used directly in hydrologic design methods; however, parameters that reflect basin shape are used occasionally and have a conceptual basis. On the other hand, Deckers(2006) suggested that catchment shape is expected to affect the hydrological process at catchment level. A number of catchment parameters have been developed to reflect basin shape. Therefore for this study, the following typical parameters were studied to acquire additional information about the similarity of the gauged and ungauged catchments.

$$Shape = \frac{H\max - H\min}{\sqrt{A}} \quad (3.3)$$

Circularity index: To estimate this ratio, the area and perimeter of the catchment were determined. The ratio is equal to unity when the shape of the catchment is perfectly circular, decrease to 0.785 when the catchment is square, and decreased when the catchment becomes elongated (Deckres, 2006).

$$CI = \frac{4\pi A}{P^2} \quad (3.4)$$

Where: P and A are perimeter (m) and area (m^2) of the catchment respectively.

Elongation Ratio: indicates how the shape of the catchments deviates from a circle. It is calculated by dividing the diameter of a circle with the same area of the catchment by the length of the catchment (Deckres, 2006).

$$EL = \frac{DC}{L} \quad (3.5)$$

Where: DC: is the diameter of the circle with the same area as the catchment, L: is the maximum length of the catchment along the main line.

2. **Modeling of the gauged catchment**

In this study, the FAO-Rainfall-Runoff modeling using WEAP model is adopted to derive model parameters and for estimation of runoff of ungauged catchment. This method determines the actual evapotranspiration using crop coefficients and the remaining of rainfall not consumed by evapotranspiration are simulated as runoff to a river via runoff/infiltration links (SEI, 2016).FAO-Rainfall-Runoff methods tend to represent the physical process in a simplified manner. It can be lumped, when catchments are considered as a single unit or distributed. Lumped models have been widely used in regionalization studies because of their limited number of parameters. Conceptual Rainfall-Runoff models are the most widely used models in regional applications even if their parameters do not necessarily have an explicit physical meaning and though they heavily rely on stream flow data for their calibration (Marechel, 2004). The reasons are their general popularity for any kind of application and their limited number of parameters to calibration.Therefore, the input parameter required for the catchment under this method were land use data, such as catchment area, crop coefficient, effective precipitation, and climate data such as precipitation and evapotranspiration. Effective precipitation is here defined as the percentage of rainfall available for evapotranspirations and the remainder is considered as runoff (Mugatsia, 2010; Singh *et al*. (2014 and 2016); SEI, 2016; Shumet and Mengistu, 2016). Effective precipitation depends on meteorological and non- meteorological parameters. Meteorological are characteristics of rainfall (amount, frequency, intensity and distribution over the area and in time), temperature, radiation, relative humidity and wind speed. Other non- meteorological parameters are: land characteristics (topography, slope), soil type (depth, texture, structure, bulk density, salt and organic matter content), and management practice (Smith, 1992). Effective precipitation of the catchment was determined using USDA Soil Conservation Service formula (see Appendix Figure 7.3). The USDA, methods combines various data in calculations: land use or cover, treatment or practice, hydrological soil class and hydrological conditions (Smith, 1992).

$$Peff = \frac{[(Ptot \times (125 - 0.2 \times Ptot))]}{125} \text{ For Ptot} < 250\text{mm} \quad (3.6)$$

$$Peff = 125 + 0.1 \times Ptot \text{ For Ptot} > 250\text{mm} \quad (3.7)$$

Where; Peff = Mean monthly effective precipitation (mm); Ptot = mean monthly precipitation (mm)

The second input data required is reference evapotranspiration.Therefore, referenceevapotranspiration of the catchment was determined using FAO Penman Monteith approach (see section 3.3.6).

The other input data is Crop coefficient. The crop coefficients of different land cover/use units are obtained from different sources as indicated on the Appendix Table, 7.5 and some assumptions are made when there are no published values. The Kc coefficient for full cover crops primarily reflects differences in transpiration as the contribution of soil evaporation is relatively small (FAO 56). After rain the effects of evaporation is predominant when the crop is small.For such lower cover conditions, the Kc coefficient is determined largely by the frequencies with which the soil surface is wetted and dried. A crop coefficient incorporates crop characteristics and average effects of evaporation from the soil. For most hydrological water balance studies, average crop coefficients relevant and more convenient than the Kc computed on a daily time step using a separate crop and soil coefficient (Yemane, 2004; Mugatsia, 2010).

NB: Every hydrological and water resources model has its own way and format to accept data. WEAP is a very flexible model which takes daily, monthly and yearly data. However, in this study the average monthly data were used for running the model. The input data were feed to WEAP model in a CSV format.

3. Model Calibration and Validation

After the model set up has been completed, the next step is to run the model and analyze the simulated result. The applicability of the model for the intended purpose was evaluated through the process of calibration and validation. Before starting with the actual calibration procedure, understanding of the influence of potential calibration parameters on the model performance are necessary. To calibrate the model, observed stream flow was used. These flows present an integrated time series of climate change in demands, water resources development and land use within the catchment. Calibration includes changing the model parameters to better simulate historic patterns

The complexity of the models and the fact that they are required to simulate human behaviors (to reflect changes in demand) in addition to physical process means the model calibration and validation is extremely difficult and has been neglected in the past (Arranzand McCartnary, 2007).

WEAP includes a linkage to a Parameter Estimation Tool (PEST) that allows the users to auto-mate the process of comparing WEAP outputs to observed data (Abdullahi, 2015; SEI, 2016). Accordingly PEST is particularly useful when the WEAP soil moisture method was used. Model can be calibrated manual, automatic and a combination of the two methods. Nonetheless, in this study PEST for automatic calibration was not used due to lack of data such as reservoir operation (currently no reservoir in the catchment) as well as soil moisture method for WEAP model was not applied. Hence, for present study a manual calibration procedure was used.

Therefore, the changes implemented were tested manually the simulated and observed time series from January 1, 1997 to December 31, 2005 until the simulated value close to the observed value. However, the first year 1997 was used to warm up the model. After the simulation result for the calibration period had fulfilled the statistical criteria, validation was performed for an independent period of records from January 1, 2006 to December 31, 2013. This period was selected for validation due to better quality of data.

4. **Model performance evaluation**

In the model calibration, the model parameters have to be adjusted until observed stream flow and simulated flow show an acceptable level of agreement.In order to evaluate the model performance relative to the observed data, the following three performance measures were used during the calibration and validation periods:

1. A good agreement between the averages simulated and observed catchment runoff (i.e. good water balance).

$$RVE = \left(\sum_{i \approx 1}^{n} \frac{Qsi - Qoi}{\sum_{i \approx 1}^{n} Qoi} \right) \times 100 \quad \% \qquad (3.8)$$

Where:

RVE = Relative Volume Error (%)

Qsi = the simulated flow (m^3/s)

Qoi = the observed flow (m^3/s)

i = is the time step, n = is the total number of time steps used

The model performance can vary between $-\infty$ and $+\infty$ but performs best when a value of 0 is generated since no difference between the observed and simulated values. The RVE between +5% and -5% indicates that the model performed well while RVE between +5% and +10% or -5% and -10% indicates the model perform reasonably (Moriasi*et al.*, 2007). However, at the same time the distribution of the discharge throughout the calibrated period may be wrong. Therefore, this criterion should be always used in combination with another criterion that considers the overall agreement of the hydrograph shape.

2. Overall agreement of the shape of the hydrograph (Nash-Sutcliffe Efficiency)

The Nash-Sutcliffe Efficiency (ENS) is used to evaluate the overall shape of the simulated and observed hydrograph. ENS measures the efficiency of the model by relating the goodness of fit of the simulated value to the observed values.

$$ENS = 1 - \frac{\left(\sum_{i\approx 1}^{n} Qoi - Qsi\right)^2}{\left(\sum_{i\approx 1}^{n} Qoi - \overline{Qo}\right)^2} \quad (3.9)$$

Where:

ENS = Nash-Sutcliffe Efficiency

Qsi = the simulated discharge (m^3/s)

Qoi = the observed discharge (m^3/s)

$\overline{Qo}$ = the average observed discharge (m^3/s)

i = is the time step

n = is the total number of time steps used.

The value of ENS ranges from one to negative infinity. The ENS indicates how well the plot of observed versus simulated value fits the 1:1 line. The closer the model efficiency is to 1, the more accurate the model and if it is between 0 and 1, it indicates there is a deviation between observed and simulated values. If ENS is negative, predictions are very poor (Nash and Sutcliffe, 1970).

3. Coefficient of Determination (R^2)

The R^2 value measures how well the simulated versus observed regression line approaches an ideal values range from 0 – 1, with a value of 0 indicating no correlation, a value of 1 representing that the predicting dispersion equals the measured dispersion (Krause *et al*; 2005).

$$R^2 = \frac{\sum_{i=1}^{n}\left[Qoi - \overline{Qo}\right]\left[Qsi - \overline{Qs}\right]}{\sqrt{\sum_{i=1}^{n}\left[Qoi - \overline{Qo}\right]^2}\sqrt{\sum_{i=1}^{n}\left[Qsi - \overline{Qs}\right]^2}} \quad (3.10)$$

Where:

R^2 = Coefficient of Determination

$\overline{Qs}$ = the average simulated discharge (m^3/s)

Qsi = the simulated discharge (m^3/s)

$\overline{Qo}$ = the average observed discharge (m^3/s)

Qoi = the simulated discharge (m^3/s)

i = is the time step

n = is the total number of time steps used.

5. Transferring calibrated model parameters of gauged catchment to ungaugedcatchment

After calibration and validation of WEAP model for gauged catchment, the final calibrated model parameters were used to estimate runoff and water balance components of ungaugedLegedara river catchment.The most common approach to transfer information from gauged to ungauged catchment is regression method when model parameters are directly related to physical catchment characteristics by means of statistical inference. This method has been extensively tested in different countries. But the results were not always convincing (e.g. Kokkonen*et al.*, 2003).Some authors conclude that it is better to directly transfer model parameters from a donor (gauged) to a receptor (ungauged) catchment than apply a statistical inference method specially catchments that are geographically continues (Vandewiele and Elias, 1995; Merz and Bloschl, 2004; Husiman*et al.*, 2003;Kokkonen*et al.*, 2003).For example,Kokkonen*et al.* (2003) used the two regionalization methods using conceptual Rainfall-Runoff model to simulate ungauged catchment runoff. The author concluded that direct transfer of calibrated model parameter from gauged to ungauged catchment is preferable than applying statistical inference if the user have full confidence to the similarity of the gauged and ungauged catchments. In this method, assume that the calibrated model parameters are constant in hydrological similar catchments. Abebe(2014) also directly transferred final calibrated model parameters from gauged Gudar catchment to ungauged An-Lemo catchment (see section 2.5). Therefore, for present study the later method was adopted.

3.3.5. Estimation of Water Balance Components of Legedara River Catchment

As defined in section 2.2, hydrologic cycle is used to express the general circulation of water in its various forms from oceans to the atmosphere, to the ground from the atmosphere, to the oceans again.In this study, the Legedara river catchment of water balance components such as areal rainfall, reference evapotranspiration, actual evapotranspiration and runoff wereestimated.

1. Areal Rainfall

Precipitation includes rainfall, snowfall, and other processes by which water falls to the land surface (Chow *et al*., 1988). Precipitation data can be used in many ways for water balance calculations. However, this input is subjected to uncertainties, as a result of measurement errors, systematic errors in the interpolation and stochastic error due to random nature of rainfall (Abeyou, 2008). Therefore, interpolation techniques of point rainfall measurement are necessary.

If the rain gauge network is uniformly distributed over an area, then a simple arithmetic average of the point rainfall data for each station could be sufficient to determine the effective uniform depth of rainfall over the catchment (Dingman, 2002). However, the gauging station in and around are few, thereforeThiessen Polygon method in Arc GIS was used to estimate areal rainfall of the catchment. Catchment mean monthly rainfall computations have been made from individual contributing station by averaging monthly rainfall values for the months and multiplying with the weighted area of each Thiessen Polygon represented by each rainfall station (Yemane, 2004).Hence, this areal rainfall is one component of water balance of the catchment and also it was used for estimation of catchment runoff.

2. Reference Evapotranspiration

The term evapotranspiration is commonly used to describe two process of water loss from land surface to atmosphere, evaporation and transpiration. Evaporation is the process where liquid water is converted to water vapor and removed from the soil surface, wet vegetation, pavements, water bodies etc. Transpiration consists of the vaporization of liquid within a plant and subsequent loss of water as vapor through leaf stomata.

Different empirical methods have been developed for determination of evapotranspiration such as, BlanenyCriddle, Radiation, Modified PenmanMonteith and Pan evaporation methods. From those, Modified Penman Monteith was considered to offer the best results with minimum possible errors in relation to a living grass reference crop. Thus it is recommended as the sole standard method in the evapotranspiration estimation (Allen*et al*., 1998)

Hence, in determining evapotranspiration of the Legedara River catchment, FAO Penman Monteith approach was used. This calculation was done using equation (3.11).

$$Eto = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} U2(es - ea)}{\Delta + \gamma(1 + 0.34U2)} \quad (3.11)$$

Where;

Eto = reference evapotranspiration, mm day^{-1}

Rn = net radiation at crop surface, MJ m^{-2} day^{-1}

G = soil heat flux density, MJ m^{-2} day^{-1}

U_2 = wind speed at 2 m height, ms^{-1}

es = saturation vapour pressure, Kpa

ea = actual vapour pressure, Kpa

es – ea = saturation vapour pressure

Δ = slope vapour pressure curve, Kpa$^{o}c^{-1}$

γ = psychometric constant, Kpa$^{o}c^{-1}$

Note: The calculation of evapotranpirationwas done using Microsoft Excel spreadsheet. For further information about the calculation procedures of reference evapotranspiration, see at the end of Appendices part.

3. Catchment Runoff

The third most important of water balance components of the catchment is runoff. As describedin section 1.2, the catchment isungauged. So, it is essential to determine the amount of water available in the system in order to state the available water resources within the catchment. Beside this, it requires understanding and properly describing water inflow and outflow from the catchment. In order to describe the movement of water, it was necessary to have rainfall data and information on runoff, evapotranspiration, infiltration etc.

In this study, calibrated model parameters of gauged catchments are transferred to ungauged catchments to estimate runoff and water balance of Legedara River catchment using FAO-Rainfall-Runoff method by WEAP model. The required input parameters are catchment area of Legedarariver, reference evapotranspiration, rainfall and final calibrated model parameters (Kc, and effective precipitation).However, Visessri(2014) suggested that scaling relationship (Area ratio) method is the simplest regionalization method, in order to use as a bench mark for assessing the performance of other commonly used regionalization method. Therefore, for present study the performance of transferring calibrated model parameters from gauged to ungauged catchment was tested by Area ratio method. Hence, flow of ungauged catchment was calculated by scaling flows of a gauged catchment according to the area ratio of the ungauged to gauged catchment.

3.3.7. Modeling of Water Demands

After knowing the available water resources within the catchment, the demand sites were added to the WEAP model and run it to allocate the water for the selected demand sites based on its priorities.

Demand analysis in WEAP is a disaggregated, end-use based approach for modeling the requirements for water consumption in an area. Using WEAP, it is possible to apply economic, demographic and water-use information to construct alternative scenarios that examine how total and disaggregated consumption of water evolve over time in all sectors of the economy. Demand analysis in WEAP is also the starting point for conducting integrated water planning analysis, since all supply and resource calculations in WEAP were driven by the levels of final demand calculated in the demand analysis (SEI, 2016). These were the waterpermit holders (domestic, industrial and environmental). Demand sites simulated in this study were based on this information.The data on demand was summed up for a catchment. Three main water use sectors were simulated in the WEAP16.01 model.

1. Domestic Water Demand

In order to model the current and future domestic water demand, current information and future projections are necessary. Therefore, in this study the total populations with an annual population growth rate were fed in to WEAP model in order to know the domestic water demand in monthly and annual bases. The water demand was computed activity levels multiplied by the water use rates of each activity (water use per unit of activity).

The World Health Organization (WHO) recommends about 100 liters of water per person per day to ensure that most basic needs are met (WHO, 2003).According to GTP-1 of Ethiopia urban and rural water supply targets were 20 and 15 liters per capita per day respectively. By keepingthese data in mind the country could not achieve full coverage with this level. Therefore, the country again developed a new standard of quantity supplied 25 liters per capita per day for rural and 40-100 liters per capita per day for urban (GTP-2, 2015). In this study, the average of water supplied 70 liters per capita per day (25.55m^3/year/capita) was used in order to determinethe current situation of domestic water demand.

2. Industrial Water Demand

Industrial water demand includes the water required for factories and industries. Despite, there is no as such big industry in the catchment, so simulationwas made by considering the future development of industry in the catchment. In the catchment, there are some industries, such as coffee washing factories, coffee processing factories and flour factories. But, none of them have been recorded water use/consumption information.MoWR(2006) recommended 5% to 10% of domestic water for industrial demand. However, the national policy advocates the transformation of agricultural lead economy to industrial lead economy. Therefore, the number of industry expected to increase in the future. By considering the future development of industry, in this study 7% of domestic water demand was adopted for the current situation as well as for thefuture industrial water demand.

3. Environmental Flow Requirement

In order to maintain the ecological management services and the natural channel habitat associate to the flow regime of Legedara river catchment, a certain reserve flows to be maintained and could be considered as sectoral water demand on its own.

A minimum flow requirement defines the minimum monthly flow required along a river to meet water quality, fish and wildlife, navigation, recreation, downstream of other requirements. Depending on its demand priorities, a flow requirement can be satisfied before, after or at the same time as other demands on the river (SEI, 2016).The FDCShift function in WEAP was used to estimate the recommended stream flow in a modified stream, by uniformly reducing (shifting) the natural (unregulated) flow duration curve by a fixed number of percentile places, and further disaggregating it in to a complete time series of modified flows.The flow duration curve is a plot that shows the percentage of time that flow in a stream is likely to equal or exceed some specified value of interest (SEI, 2016).FDCShift is one of the several possible approaches to calculating environmental flows, and should be considered a “low confidence” method.

The FDCShift was calculated according to the following procedures (Abdullahi, 2015; SEI, 2016).

1. The flow duration curve (FDC) was calculated from the original (“No change”) stream flow time series specified by FDCShift Wizard parameters.
2. For each flow value Q in the original stream flow time series, calculate its percentile P in the FDC: P = 100×Rank/ (N+1), where N is the number of data points and Rank is the rank order (from 1-N) of Q in the flow duration curves(flow in decreasing order). Rank = 1 is the highest flow, Rank = N is the lowest flow.
3. Calculate a new percentile P by shifting P the number of steps according to the environmental management class parameters (A-F, corresponding to a shift of 1-6 steps). A shift of one step corresponds to moving from one number to the next larger number in the following list of percentile. 0.01%, 0.1%, 1%, 5%, 10%, 20%, 30%,

40%, 50%, 60%, 70%, 80%, 90%, 95%, 99%, 99.9%, and 99.99%. For example a shift of 2 places (B slightly modified) would mean that a 60% flow would be reduced to 80% flow, and a 90% flow would be reduced to a 99% of flow.

3.3.8. Priorities for Water Allocation

Water allocation is a process of sharing the available water resources among various regions and computing users. In simple terms, it is a mechanism for determining who takes water, how much they can take, for which locations, when and for what purpose (Abdullahi, 2015; SEI, 2016).WEAP use a liner programming techniques to solve the water allocation model. Priorities (1 to 99) were used to classify demands. 1 represents highest priority demand node and 99 represents the lowest priority demand node (SEI, 2016).In this study, the following priorities were adopted in order WEAP to understand which demand sector should be given priorities.

a. Domestic water demand first priority
b. Industrial water demand first priority
c. Environmental flow requirement first priority

NB: During model setup, all the selected demand sites were assigned equal priorites in order to understand the potential of water resources relation with the booming demands.

3.3.9. Developmentof Scenarios.

Based on different sets of future trends and factors that affect water supply and demands,scenarios weredeveloped. The scenariosisused to address a lot of "what if situations", like what if population growth change, what if annual water use rate will be changed and what if raifall will be changed.With regards to the availability of the water resources, for the studyarea scenarios were evaluated. The results that were generated from the development of scenarios can help the water resources planner indecision making, which is the core of this study. WEAP uses scenarios as a way to evaluatedifferent water allocation schemes, given water demand and associated priorities.

All scenarios have been inheriting data from the Current Accountsyear. For present study, six scenario including reference scenario were developed based on current situation and future water demands.

1. Reference scenario

Reference scenario represents the changes that are likely to occur in the future without interventions or new policy measures(Abdullahi, 2015; SEI, 2016).In this scenario, no changes were made except the incremental of population growth. Therefore, What will happen if the current situation contionos as it is?

2. Scenario one: High population growth rate

In order to understand the available water resources of the catchment relations to the future water demandfrom 2017-2040 scenario one was developed to alter reference scenario. According toMoWR (2006) report, indicated that there is a clear trend of population growth. Therefore, what will happen if the population growth rate is higher than the reference scenario population growth rate?In this case, the population growth rate was raised to 5% to simulate the water demand in the future. However, other variables are constant.Thus, population was projected from 2017 – 2040 using WEAP model by means of the built-in "Growth From". However, for projecting the future population 2016 was considered as a base year.The projected population is depicted on Appendix Figure,

3. Scenario two: Low population growth rate

In thsis scenario, what will happen if the reference population growth lowered to 3%?

4. Scenario three: High annual water use rate

According to the report of MoWR (2006) indicated that there is a clear trend of urbanization. The increase in population that turned is due to migration of people from rural to urban area. Therefore, the report indicated that the average per capita water demands are raising too, just based on a change in lifestyle and water supplies.In this scenario because of urbanization the water requirements per person per year have been giving consideration, based on the expected future development of Ethiopia. Therefore, what will happen if the annual water use rate of the reference scenario will be increased to $36.5m^3$/year/capita?

5. Scenario four: Low annual water use rate

Abdullahi (2015) mentioned that improving water use efficiency through demand side management is considered an important activity towards saving the available water resources.

In this scenario, demand management approach was applied in order to use the available water in the catchment efficiency by reducing the annual water use rate from 25.55m^3/year/capita to 18.25m^3/year/capita due to demand side management programs.

6. Scenario five: Rainfall change

The most rational way to assess the impact of future rainfall change on the runoff of a river catchment would be through the implementation of GCM. However, the assessment of the impact of future raifall changes on the catchment runoff of this scenario is meant only to give an insight to what extent if the future catchment rainfall increased or reduced from the current value. What will happen? Therefore for present study, the impact of future rainfall change on catchment runoff generation has been assessed by changing the rainfall values arbitrarily by 5% and 10% higher or lower than the actual value

3.3.10. Calculation Algorithm

WEAP uses a hierarchical structure to disaggregate water demand data. One can easily adopt this structure to the nature of the problem and data availability. A demand site is needed for water and it is calculated as the sum of consumptions for all demand sites bottom level-branches (Br).

Annual Demand = Total Activity level Br × Water use rate Br…(3.12)

The total activity level for a bottom level branch is the product of the activity level in all branches from the bottom level back up to the demand site branches.

Total activity level Br = Activity level Br × Activity level Br’ × Activity level Br’’ ×.(3.13)

Where; Br is the bottom level branch, Br’ is the parent of Br, Br’’ is the grandparent of Br.

Monthly Demand: To specify the demand for each month using the ReadFromfile function, or by entering direct in WEAP using the monthly time series wizard.

Inflow and outflow of water: this step computes water inflows to and outflows from every node and link in the system in monthly time steps. This including calculating withdrawals from supply sources to meet demands.

In the FAO-Rainfall-Runoff (Simplified Coefficient) method runoff of the catchment can be calculated with the following equation (Singh *et al*., 2016; SEI, 2016).

$$R = \max\left(0, PAET - ETc\right) + \left(P \times \left(1 - Peff\right)\right) \quad (3.14)$$

$$PAET = P \times A \times 10^{-5} \times Peff \quad (3.15)$$

$$ETc = ETo \times Kc \times A \times 10^{-5} \quad (3.16)$$

$$ETa = \min\left(ETc, PAET\right) \quad (3.17)$$

Where;

A (ha) = catchment area

P (mm) = Precipitation

Peff (%) = percentage of precipitation that can be used for evapotranspiration

PAET(MCM) = precipitation available for evapotranspiration

Kc (-) = crop coefficient

ETo(mm) = reference evapotranspiration

Etc (MCM) = Potential crop evapotranspiration

ETa(MCM) = Actual evapotranspiration

R (MCM) = catchment runoff

3.4. Methods of Data Analysis

In order to extract required information and desired results from the available data, both statistical instruments and software application was used. To estimate runoff and water balance components of Legedara river catchment; transferring calibrated model parameter from gauged to ungauged catchment was used by FAO-Rainfall-Runoff model. Based on the availability of the model with its capabilities for analysis and works in any environment, data was analyzed by using WEAP Model version 16.01 to manage the available water in an efficient and sustainable manner among water users in Lagadara River catchment. ArcGIS 10.1 was used for geo-processing and overlaying of spatial data as compatible to the WEAP model.

4. RESULTS AND DISCUSSION

As described in section 1.2, the catchment is ungauged. Therefore, prior to estimating water balance components of Legedara river catchment, the following steps were done.

1. **Selection of representative catchment and catchment characteristics**

In this particular study, Waleme river catchment was selected in order to transfer calibrated model parameter to Legedara river catchment. UngaugedLegedara (A) and gauged Waleme(B)rivercatchment, as shown in Figure 4.1 covered the total drainage area of 94.87 km^2 and 81.34km^2respectively.

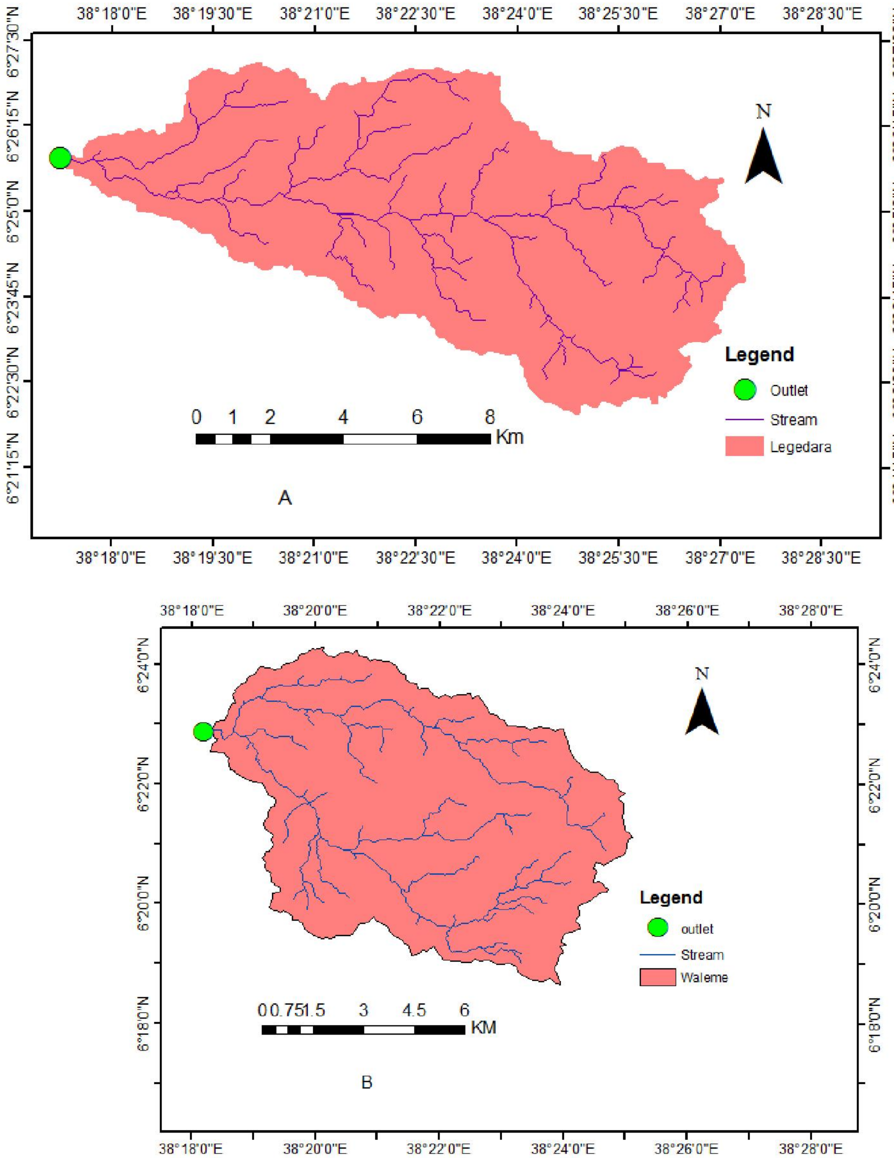

Figure 4- 1: UngaugedLegedara (A) and gauged Waleme(B) rivercatchment

Referring Figure 4.2, 4.3 and 4.4 of Legedara river catchment have been similar land cover, soil type, and slope range with Waleme river catchment.

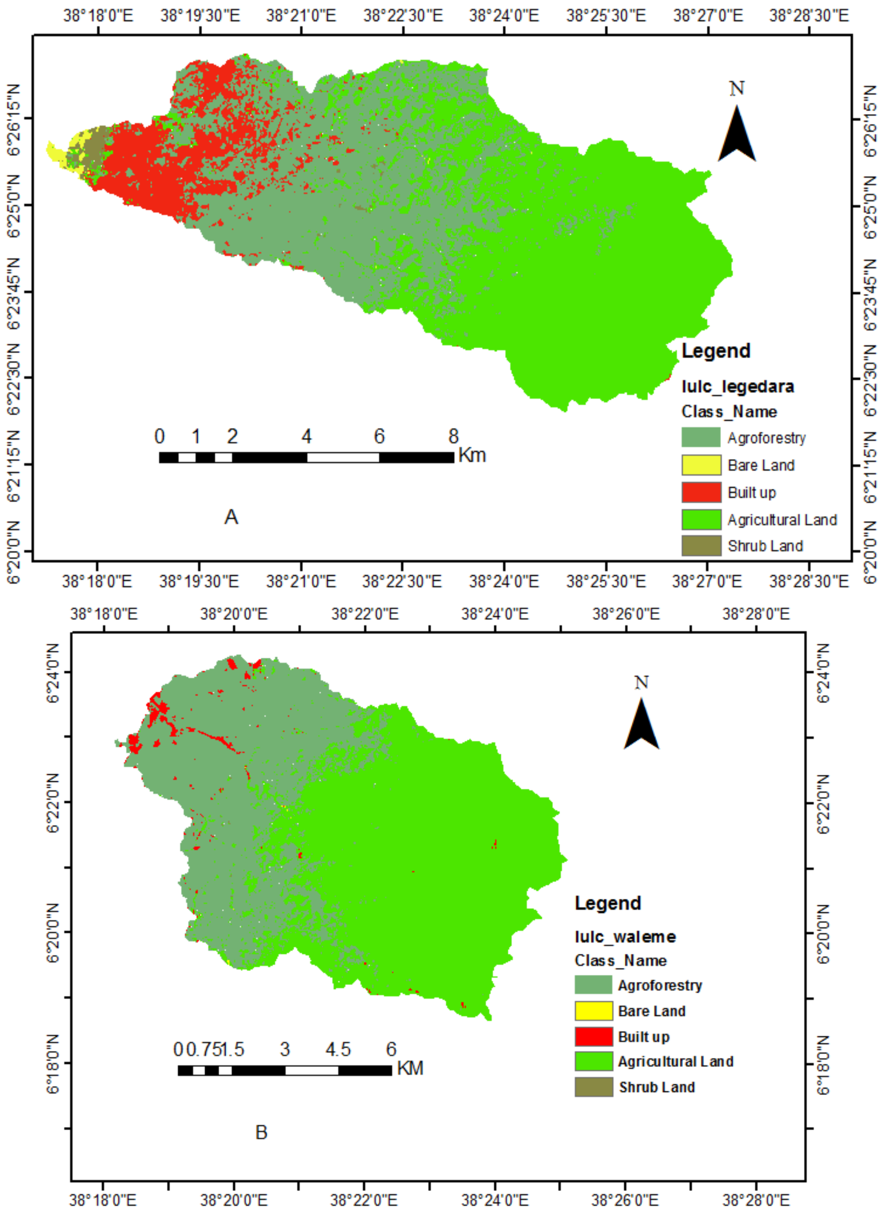

Figure 4- 2: Land cover/use map of Legedara (A) and Waleme(B)rivercatchment

Land cover has been shown in several studies to affect flow characteristics of the catchment (e.g.Kebede, 2010;Daniel, 2010).Therefore,as it can be observed in Figure 4.2, most portions of the two catchments were covered with agricultural land and agro-forestry, which accounts 51.43% and 59.01% of agricultural land 36.86% and 39.66% of agro-forestry from the total area of Legedara and Waleme river catchment respectively. Built up, covers some portions of the catchments, which accounts 10.45% and 1.3% from the total area ofLegedara and Waleme river catchments. Other portions are covered with bare land and shrub land. Therefore, one main consideration of catchment selection criteria was fulfilled.

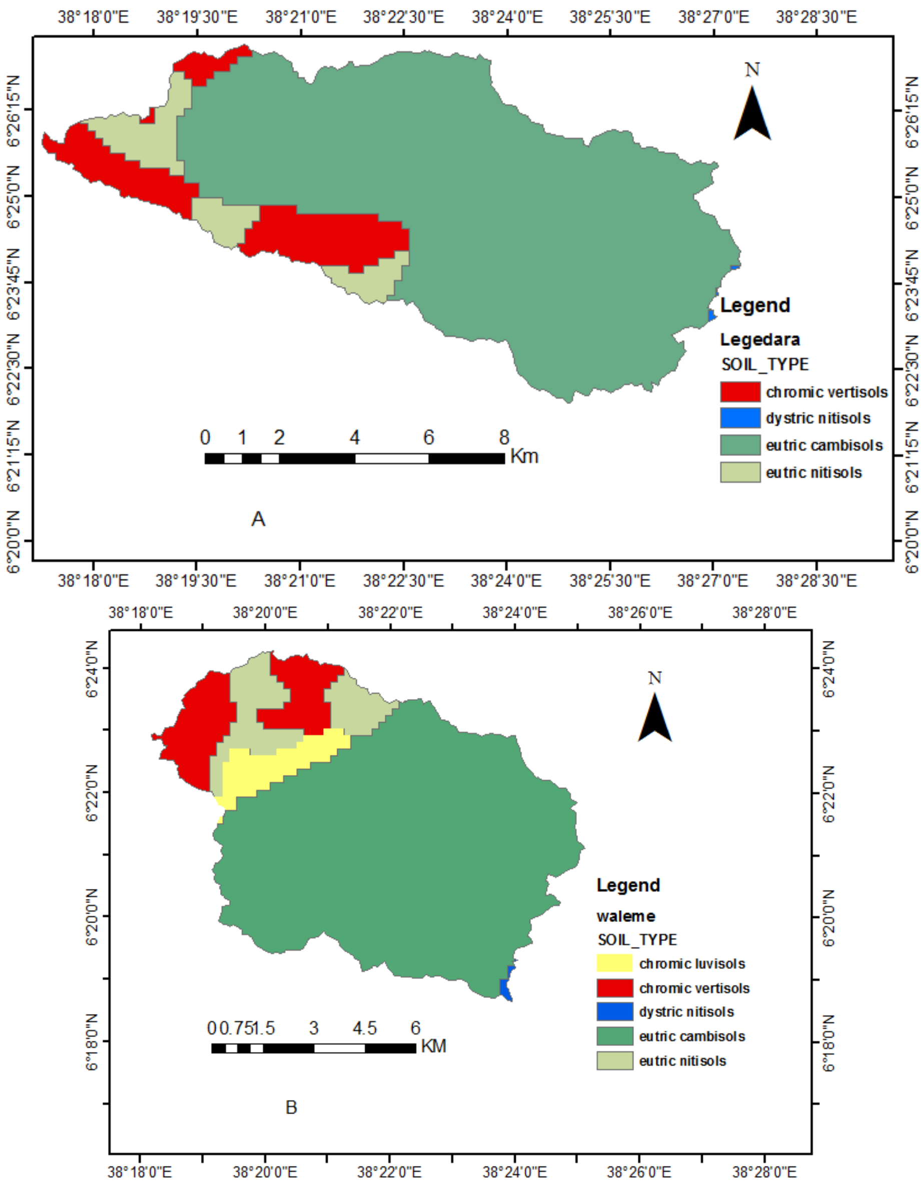

Figure 4- 3: Soil map of Legedara (A) and Waleme(B)rivercatchment

The major soil units classified in the Legedara and Waleme river catchments were: EutricCambisols, Chromic Vertisols, EutricNitosols and Dystricnitosols. EutricCambisols, covering an area of 77.56 km^2 and 61.96 km^2, which accounts 81.76% and 76.20% of the total area of Legedara and Waleme catchment respectively. Chromic Vertisols, cover some portions of the catchments, which accounts 11.08% and 10.13% from the total area of Legedara and

Waleme river catchments respectively. Other portions of the two catchments were covered with EutricNitosols and DystricNitosols, which accounts 6.64% and 7.11% of EutricNitosols and 0.08% and 0.20 % of DystricNitosols from the total area of Legedara and Waleme river catchment respectively. Chromic Luvisols, cover an area of 3.82% of Waleme river catchment, but the characteristics of this soil unit is also similar to other listed soil units of the Legedara river catchment.

Therefore, the second main consideration of catchment selection criteria was fulfilled

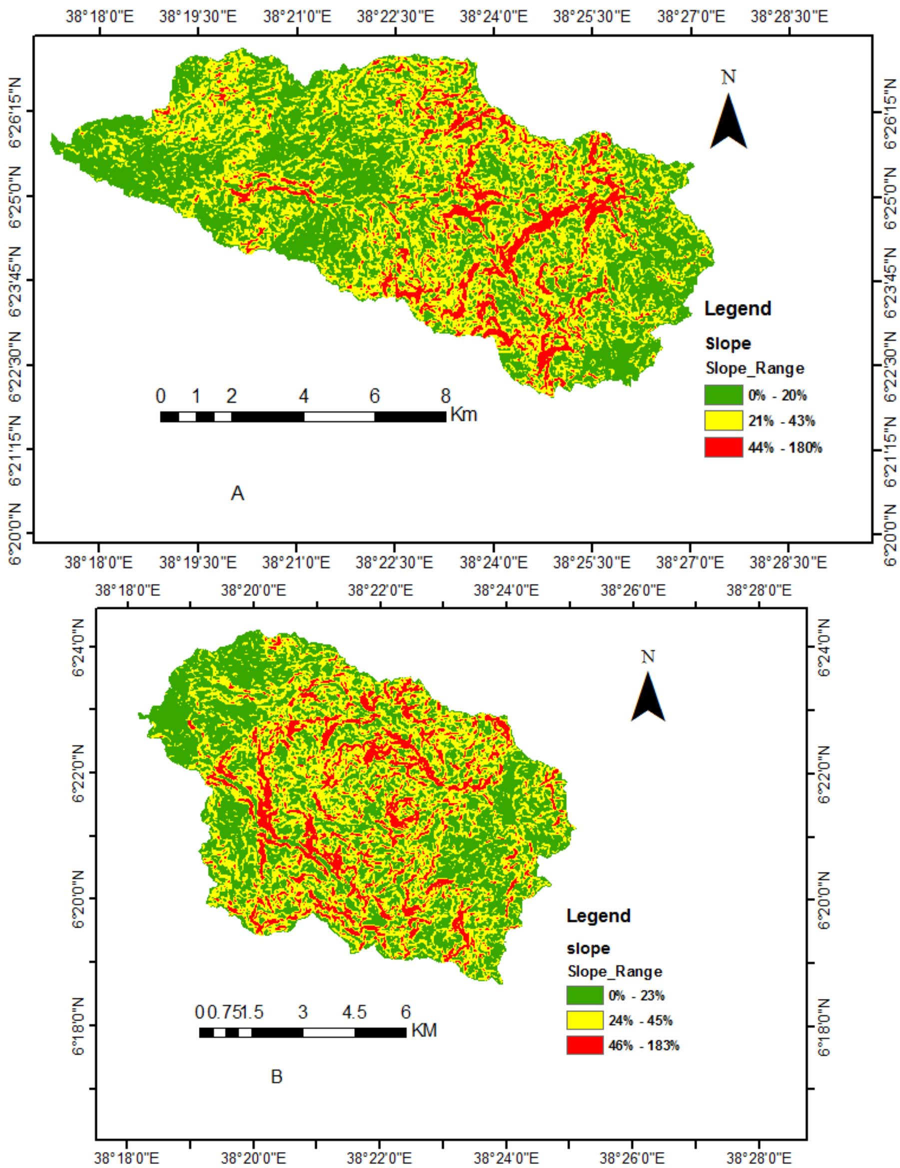

Figure 4- 4: Slope map of Legedara (A) and Waleme (B) rivercatchment

Slope is an important characteristic of a catchment as it gives an indication of the kinetic energy available for water to move towards the catchment outlet, and it has been found to be related to total runoff of the catchment (Mazvimavi, 2003). Therefore, as it can be observed in Figure 4.4, the slope ranges of the two catchments covers similar portions. Therefore, the third main consideration of catchment selection criteria also fulfilled. Winter (2001) suggested that area having similar land slope, land use,soiland climate results similar hydrological flow path regardless of the geographical location of the site.

Other main considerations, such as the geographical boundary of ungaugedLegedara river catchment and gauged Waleme river catchment are geographically continuous (see Figure 3.2) and the length of year recording of stream flow of Waleme river at Sala, near Dilla university station was about 17 years (see Appendix Table7.3).

In general the result of other climateand physical catchment characteristics of Legedara and Waleme river catchments were depicted on Table 4.1.

Table 4- 1: Climate and physical characteristics of Legedara and Waleme rivercatchment

No	Climate and Pccs	Legedara river catchment	Waleme river catchment
1	Rainfall pattern	Bimodal	Bimodal
2	Peak rainfall season	April/May and September/October	April/May and September/October
3	Dry rainfall season	January, February and December	January, February and December
4	Annual rainfall (mm)	1316.42	1307.11
5	Max elevation m.a.s.l (m)	2999	3003
6	Min elevation m.a.s.l (m)	1427	1507
7	Area (km^2)	94.87	81.34
8	Perimeter (km)	52.55	45.35
9	Average elevation m.a.s.l (m)	2213	2255
10	Hypsometric integral	0.50	0.50
11	Longest flow path (km)	24.036	18.058
12	Elongation ratio (-)	0.46	0.56
13	Circularity index (-)	0.43	0.49
14	Catchment shape	5.10	5.24

Several researchers have concluded that geographical proximity does not guarantee hydrological similarities, other criteria also meet such as land cover, soil type, slope range, elevation, climate characteristics and data availability(Kokkonnen*et al*., 2003; Mazvimavi, 2003; Marechal, 2004;Merz and Bloschl, 2004;Deckers, 2006; Abeyou, 2008;Perera, 2009Kebede, 2010; Tewodros, 2012).Therefore, almost all the criteriasuggested by different researchers were fulfilled for the purpose of transferring information from gauged Waleme to ungaugedLegedara river catchment. As can be observed from Figure 4.2, 4.3, 4.4 and Table 4.1, both Waleme and Legedara river catchments were found almost similar hydro-meteorologically.

2. **Modeling of gauged catchment**

In order to derive calibrated model parameters, FAO-Rainfall-Runoff modeling using WEAP model was developed for Waleme river catchment. Therefore, land use (area of catchment, Kc and effective precipitation), and climate data (precipitation and evapotranspiration) were feed in to WEAP model. In setting up the WEAP model, catchment sites generated the input for Waleme river catchment (see Appendix Figure 7.6). Using the FAO-Rainfall-Runoff method the land use and catchment characteristics were defined. The other input options at the catchment sites: ‘lose and reuse’, ‘yield’, ‘water quality’, and ‘cost’ were not considered in this study.

3. **Model calibration and validation**

The observed stream flows for the period 1997-2005 were used to calibrate the model, and 2006 - 2013for validation. However, the first year 1997 was used to warm up the model. The results presented in Figure 4.5 indicate that the model is able to predict the catchment runoff. However, this result was obtained after variation of land use factors (Kc and effective precipitation).In calibration, the land use factors (Kc and effective precipitation) were modified within the allowable limits. The average Kc values of the catchment were modified within the limits of FAO Irrigation and Drainage 56 guidelines. Effective precipitation was added or reduced by 10%to 20%, by trial and error. Therefore, the model performance was evaluated using Nash-Sutcliffe Efficiency (ENS), Coefficient of Determination (R^2) and Relative Volume Error (RVE).

Table 4- 2: Summary of model performance for calibration period

Period	Annual flow (m^3/s)		Monthly model efficiency measures		
	Observed	Simulated	ENS	R^2	RVE (%)
1998 – 2005	24.45	23.82	0.81	0.86	-2.64

Calibrated result in Nash-Sutcliffe Efficiency (ENS) 0.81, Correlation Determination (R^2) of 0.86, and Relative Volume Error (RVE) of -2.64% showing a good agreement between observed and simulated monthly flows.

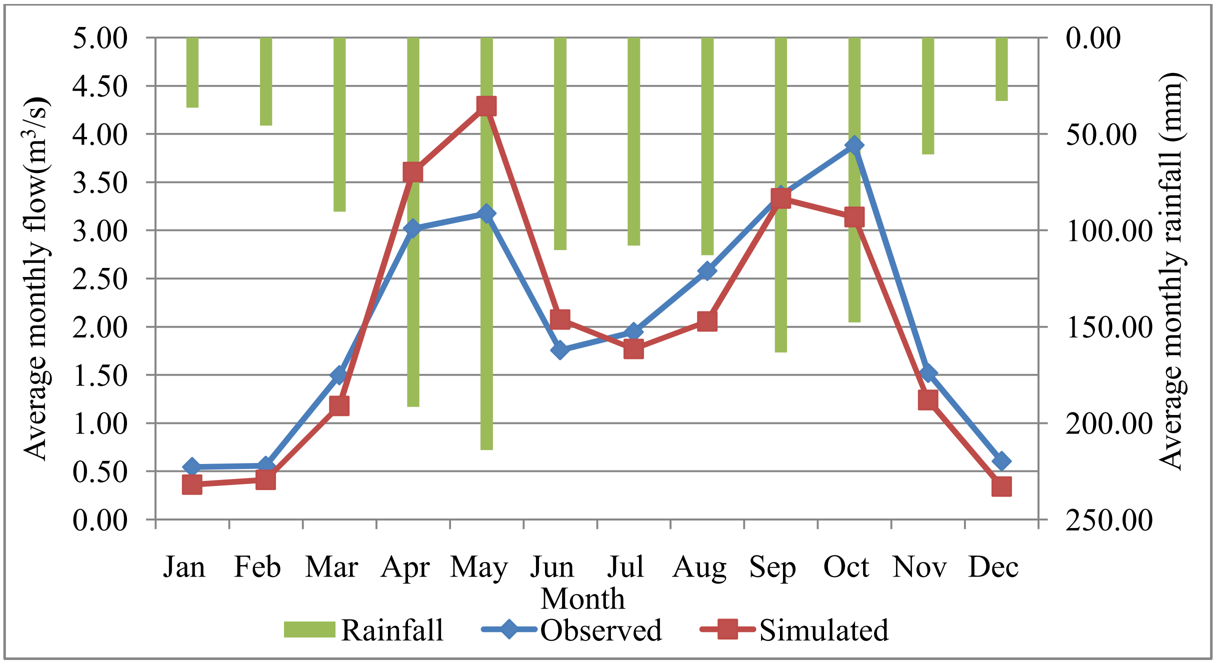

Figure 4- 5**:** Hydrograph of the observed and simulated monthly flow for the calibration period

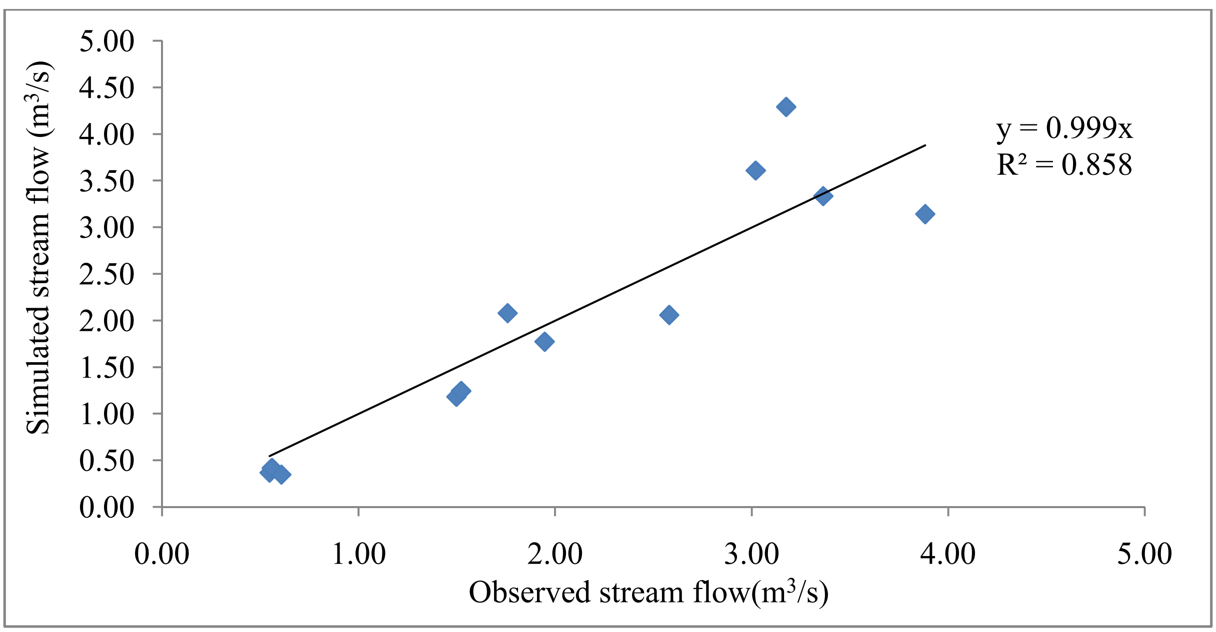

Figure 4- 6: Scatter plot of Simulated Vs Observed stream flow for calibration

WEAP with calibrated parameters was validated using an independent set of stream flow data for a period 2006 – 2013. The validation involves model run with unchanged parameters set.

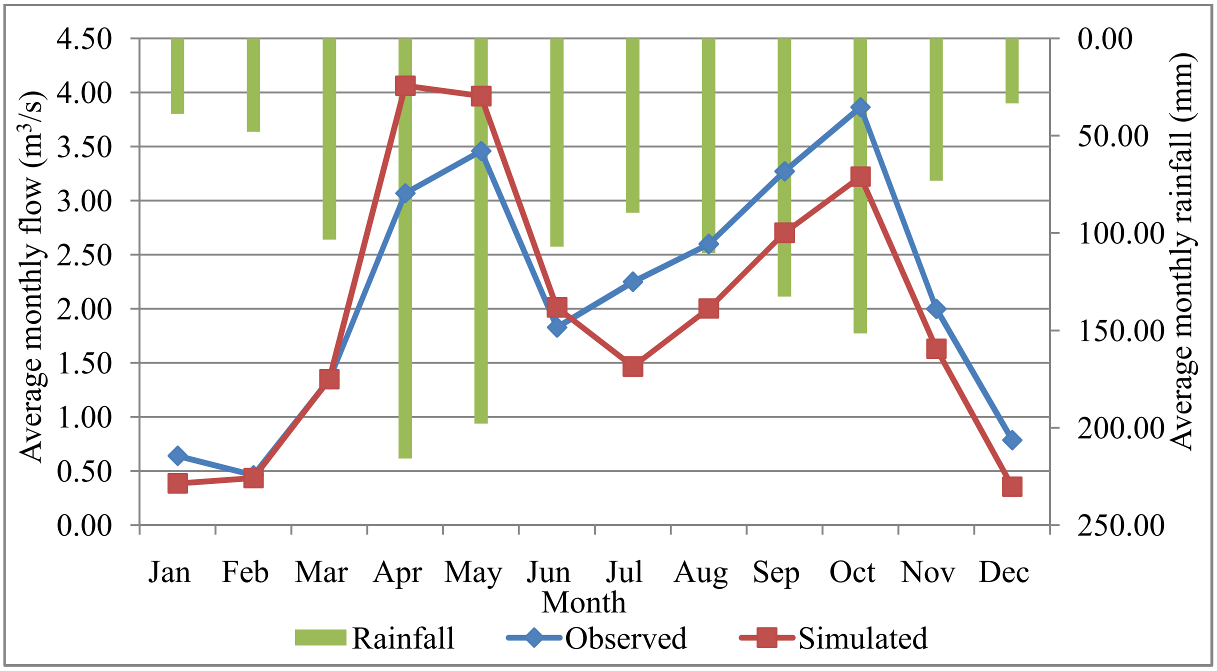

Figure 4- 7: Hydrograph of the observed and simulated monthly flow for the validation period

Table 4- 3: Summary of model performance for validation period

Period	Annual flow (m^3/s)		Monthly model efficiency measures		
	Observed	Simulated	ENS	R^2	RVE (%)
2006 – 2013	25.58	23.61	0.77	0.83	-7.73

Accordingly, good agreement between monthly observed and simulated flows (Figure 4.7)in the validation period the Correlation Determination (R^2) 0.83, Nash-Sutcliffe Efficiency (ENS) 0.77 andRelative Volume Error (RVE) -7.73%.The result also indicated that the model was able to simulate monthly catchment stream flow.

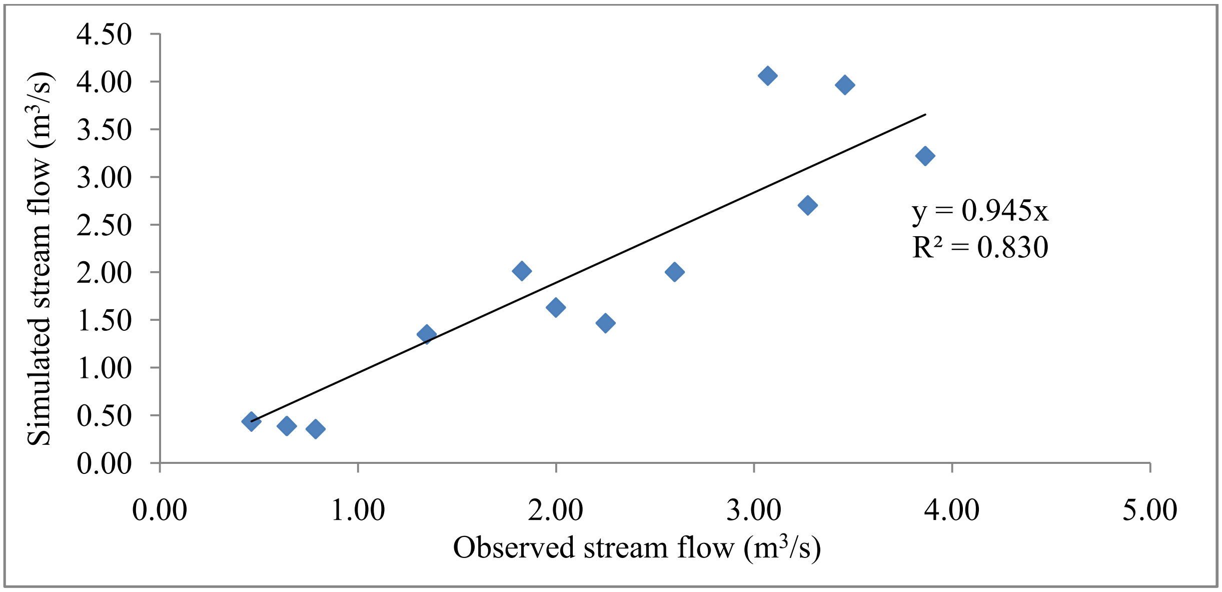

Figure 4- 8: Scatter plot of Simulated Vs Observed stream flow for validation

Figure 4.5 and 4.7 demonstrates that, the simulated flow follow the trends of observed flows, however the simulated flows in some months of the calibration and validation period were underestimated. This may be due to the limited weather data and flow data used as input to the model.Although, the simulated flows some peak than observed flow, this may be due to excess rainfall being attributed to runoff or it may be an indicators of abstraction of water from the river before reaching the measured point. The other reason may be the runoff of the catchment is simulated by using FAO-Rainfall-Runoff (Simplified Coefficient) method with land use data (catchment area, Kc, and effective precipitation) and climate data (precipitation and reference evapotranspiration), and only Kc andeffective precipitation were used for calibration and validation of the model. This is suggested by Mugatsia(2010); Singh*et al.*(2014 and 2016); Abdullahi(2015) calibrated parameters are limited also pointed out that soil moisture method with more detailed data should be used to model the hydrology of the catchment by WEAP model. It is obvious that, there is some weakness in this FAO-Rainfall-Runoff method.

The model as indicated in Figure 4.5 and 4.7, most of the times underestimates runoff during dry month and over estimates in wet months is observed. This is due to the fact that Rainfall-Runoff method as explained in Mugatsia(2010), underestimate the runoff during dry month and overestimate in wet season and also the method assume, runoff occurred after satisfying evapotranspiration (SEI, 2016).Deckers(2006) also suggested that the conceptual Rainfall-

Runoff methods often perform well during the peak of the wet season rather than the beginning or end of the season in which the problem of over or under prediction became more critical. All Rainfall-Runoff models currently in use merely are approximation of the real world hydrological processes taking place at catchment scale and none of them are able to completely describe these actual processes (Abeyou, 2008;Perera, 2009; Bogale, 2011), which is also the case forFAO-Rainfall-Runoff model.

In general, good performance of the model in the validation period indicates that, the parameters during calibration period can be taken as representative sets of Waleme river catchment and this calibrated model parameters weretransferred to Legedara river catchment for estimation ofrunoff and water balance of the catchment.

Singh *et al*.(2014 and 2016)also suggested that WEAP model was performing satisfactory for simulation of runoff using FAO-Rainfall-Runoff (Simplified Coefficient) method and finally the author concluded that, the final calibrated model parameters (Kc and Effective precipitation) can be applied for runoff simulation inother river basin with similar hydro-meteorological condition.

Table 4- 4: Final calibrated model parameters

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Set	Oct	Nov	Dec
Kc	0.30	0.50	0.60	1	1	1	0.9	0.75	0.83	0.65	0.40	0.30
Peff (%)	67	73	57	40	34	40	46	40	35	30	60	67

4.3. Water Balance Components of Legedara River Catchment

The determination of the water balance components of the catchment has played a great contribution in water resources and demand management. A water resources development plan that is carried out on the basis of this water balance information to minimize risk and mismanagement, and this led to proper utilization of water resources of the catchment.

Despite all uncertainties, the catchment water balance components such as areal rainfall reference evapotranspiration, actual evapotranspiration and runoff were estimated for this particular study.

1. Areal rainfall

Mean areal rainfall of the catchment was calculated by Thiessen Polygon method using Arc GIS 10.1. Figure 4.9 show Thiessen Polygon map of catchment inside and around the study area. The catchment is influenced by two rain gauge stations namely Kebado and Dilla station. As it can beobserved from the map, the contribution of rainfall of Dilla station is smaller even it is not visible to see.

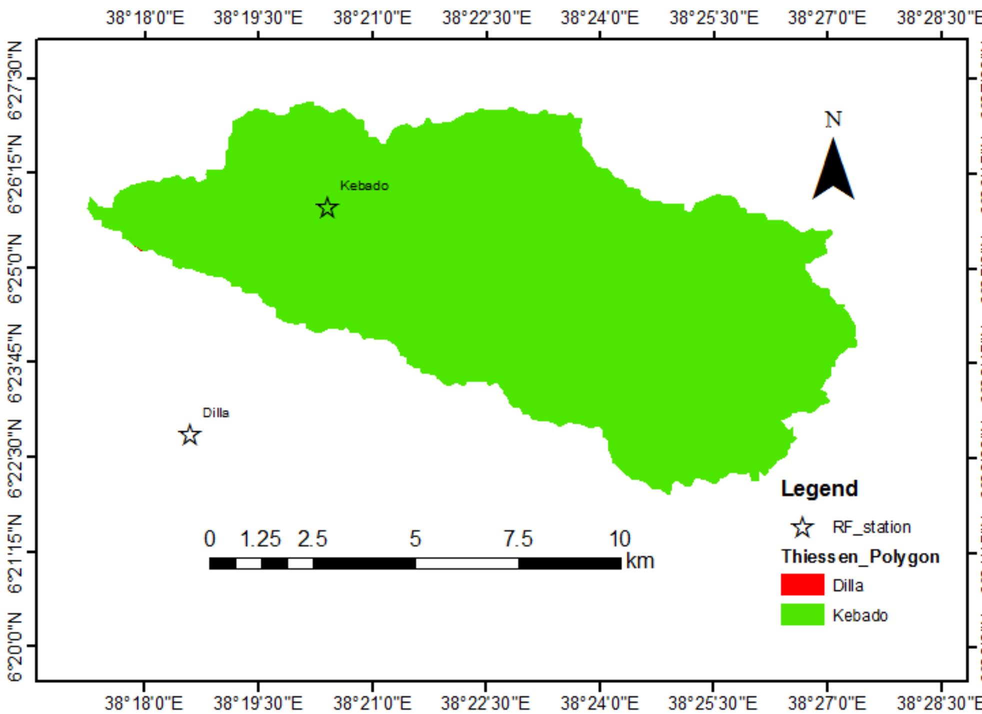

Figure 4- 9: Thiessen Polygon map showing the contribution of rainfall stations to the catchment

The average monthly areal rainfall depth for the year of 1997 – 2013 of the catchment was obtained, and the result is depicted on Figure 4.10. As a result of the calculation, based on Thiessen Polygon method, it was found that the average annual areal rainfall depth of the catchment is equal to 1316.42mm.

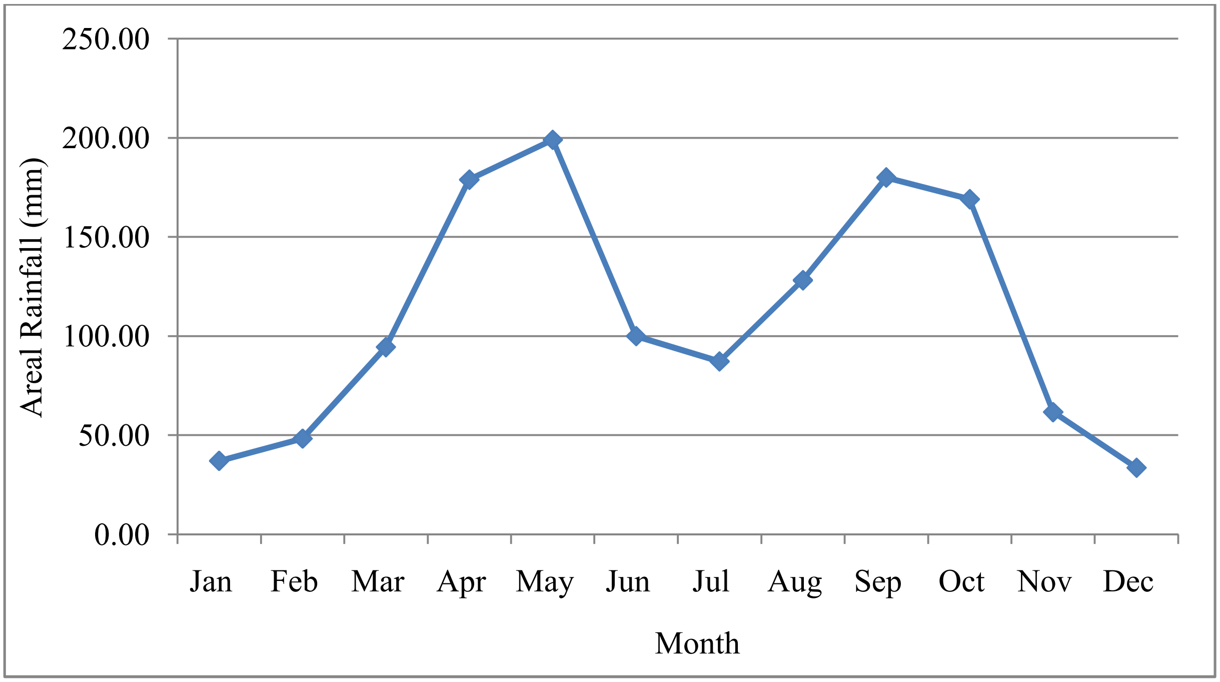

Figure 4- 10: Mean areal rainfall distribution of the Legedara river catchment (1997 – 2013)

The distributions of rainfall vary not only from month to month, also from year to year. The monthly distribution of rainfall of the catchment is bimodal characteristics with the first wet season occurring in around April/May and the second season in September/October. From Figure 4.10, it is easy to see the months with lower rainfall in Legedara river catchment.Therefore, theminimum rainfall for the study area wasrecorded in January, February and December, which accounts about 9% of the total annual rainfall of the catchment, whereas the intermediate rainfall was recorded in March, June, July, August and November, which accounts about 35.7% of the total annual rainfall of the catchment. On contrary in April, May, September and October there was a highest rainfall distribution throughout the catchment, which accounts about 55.3% of the total annual rainfall of the catchment.

As suggested byChow *et al*.(1988)the variation in the seasonal distribution of the rainfall is attributed to the position of Inter Tropical Convergence Zone, the relationship between upper and lower air circulation, the effect of topography and the role of local convection currents and the amount of rainfall.

2. Reference Evapotranspiration

The average monthly reference evapotranspiration of the catchment for the year of 1997 – 2013was calculated, and the result is depicted on Figure 4.11. As a result of the calculation, based on FAO Penman Monteith, it was found that the average annual Reference evapotranspiration of the catchment is equal to 1142.07 mm.

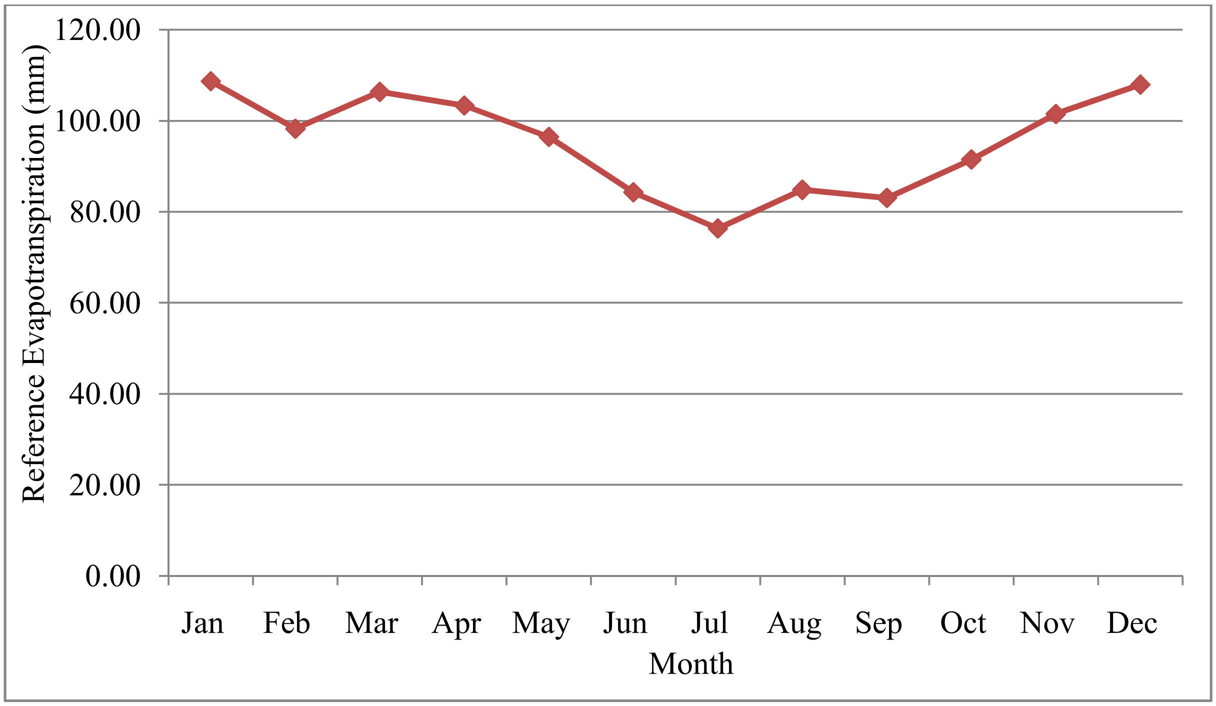

Figure 4- 11: Mean monthly reference evapotranspiration of the Legedara river catchment

From Figure 4.11, it isstraightforward to see the months with very high potential evapotranspiration in the catchment.Therefore, the maximum potential evapotranspiration was observed in January, Marchand December. The intermediatepotential evapotranspiration was occurred in February, April, may, Octoberand November while in June, July, August and September there was a lowerpotential evapotranspiration throughout the catchment.

3. Actual Evapotranspiration

Actual evapotranspiration is dynamic parameter which fluctuates based on weather conditions, types of land cover and water availability. Hence, the amount of actual evapotranspiration is limited either by the available water or the energy (Visessri, 2014). Therefore, the actual evapotranspiration of the Legedara river catchment was determined based on those dynamic parameter considerations and the average mean monthly actual evapotranspiration of the catchment is depicted onFigure 4.12.

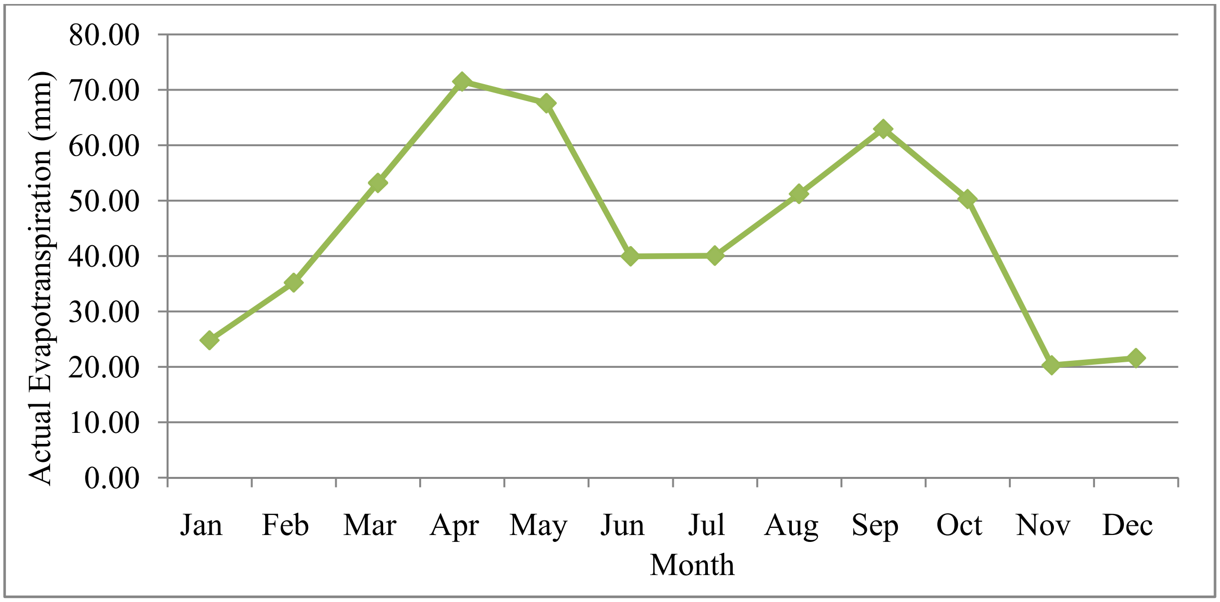

Figure 4- 12: Mean monthly actual evapotranspiration of the catchment (1997– 2013)

As can be observed from Figure 4.12, the actual evapotranspiration vary from month to month.

4. CatchmentRunoff

Taking the catchment similarity in to account, runoff of Legedara river catchment was estimated using FAO-Rainfall-Runoff model. The results were depicted on Figure 4.13. However, for assessing the performance of transferring calibrated model parameters from Waleme river catchment to Legedarariver catchment, scaling relationship (Area ratio) methods was used as suggested by Visessri (2014).As a result of the calculation, based on FAO-Rainfall-Runoffand Area ratio method, it was found that the average annual runoff of the catchment is equal to 73.83 Million Cubic Meter (MCM) and 77.1MCM respectively.The result shows, a good relation between the simulated runoff by the method of transferring calibrated model parameters and area ratio method. The results of the two methods were depicted on Appendix Figure 7.4 and 7.5.

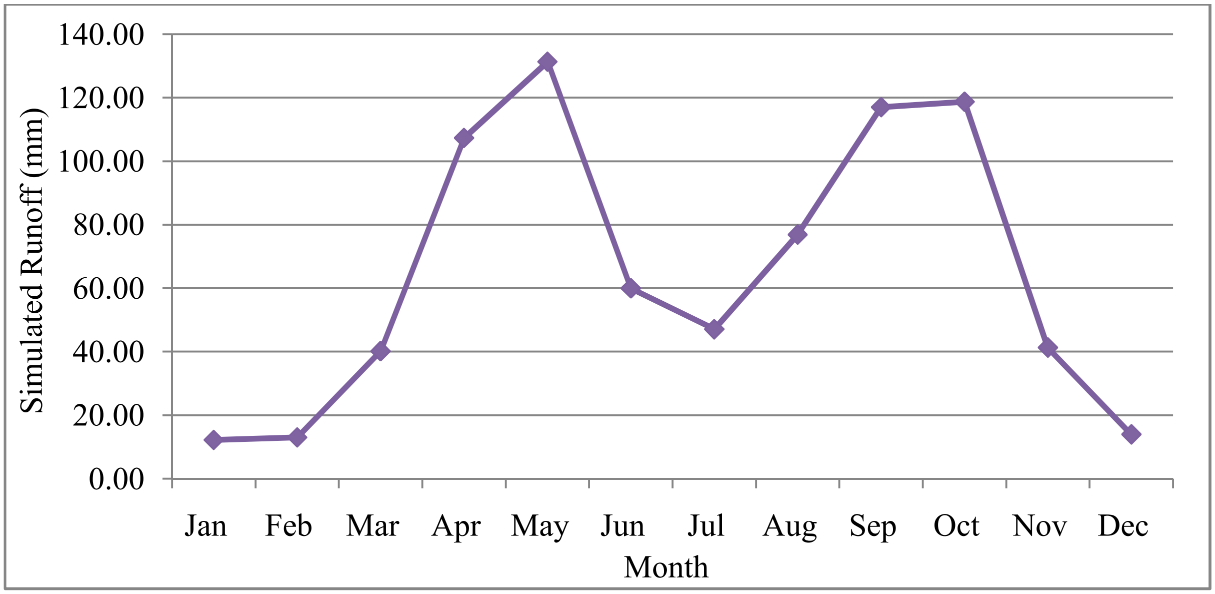

Figure 4- 13: Mean monthly simulated runoff of Legedara river catchment (mm)

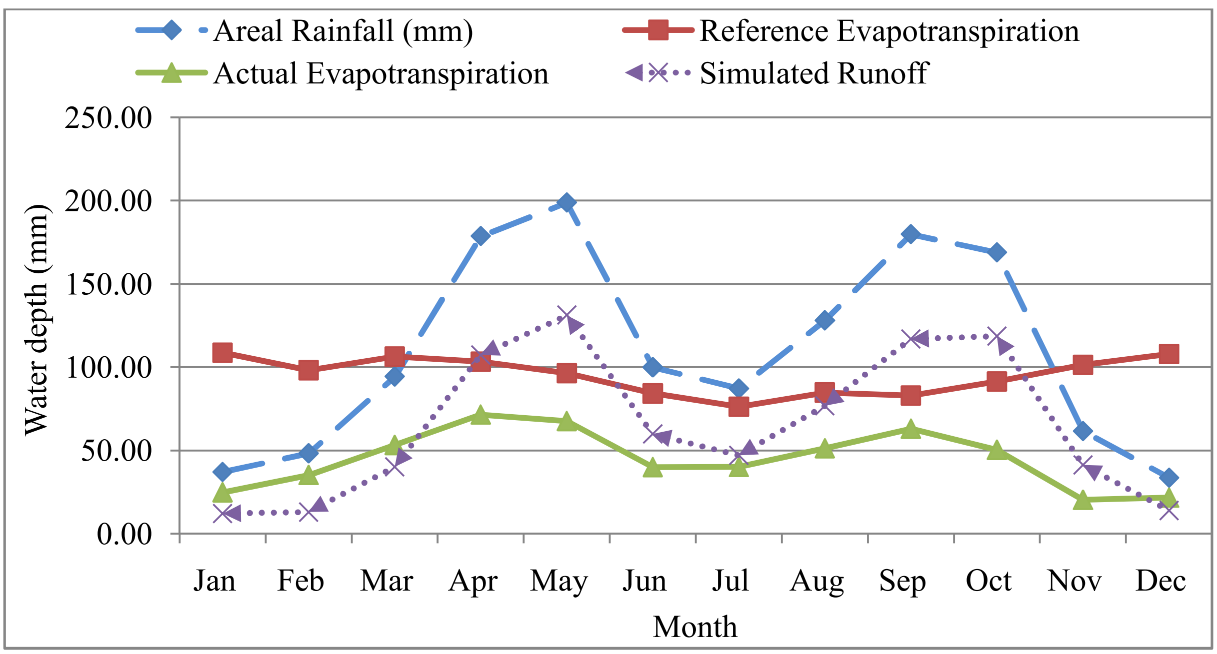

Figure 4- 14: Mean monthly water balance component of Legedara river catchment (1997-2013)

Despite all uncertainties, as a result of data preparation (filling of missing data, calculation), measurement of meteorological data and hydrological data of errors, transferringcalibrated model parameter from gauged catchment to ungauged catchment, and land cover classification, and also the model performance,the long term catchment water balance were estimated separately. Accordingly annual long term (1997 – 2013) average areal rainfall, reference evapotranspiration, actual evapotranspiration and runoff are estimated as 1316.42mm, 1142.07mm, 538.78mm and 778.65mm respectively.

In general, in humid and highland area the amount of runoff for a given storm depends on the total amount of effective rainfall (Amy, 2009). Accordingly, as successively more rainfalls occurred, more and more runoff is produced.As can be observed in Figure 4.14 the amount of rainfall is high and also the study area wascharacterized with humid and highland area. Therefore, in Legedara river catchment the amount of runoff produced at the outlet is higher.

4.2. Modeling of Water Resources and Demands of the Catchment

The WEAP model performs a mass balance of flow sequentially down a river system, making allowances for abstraction. The WEAP model for Legedara river catchment was setup to simulate the water resources and demands of the catchment.

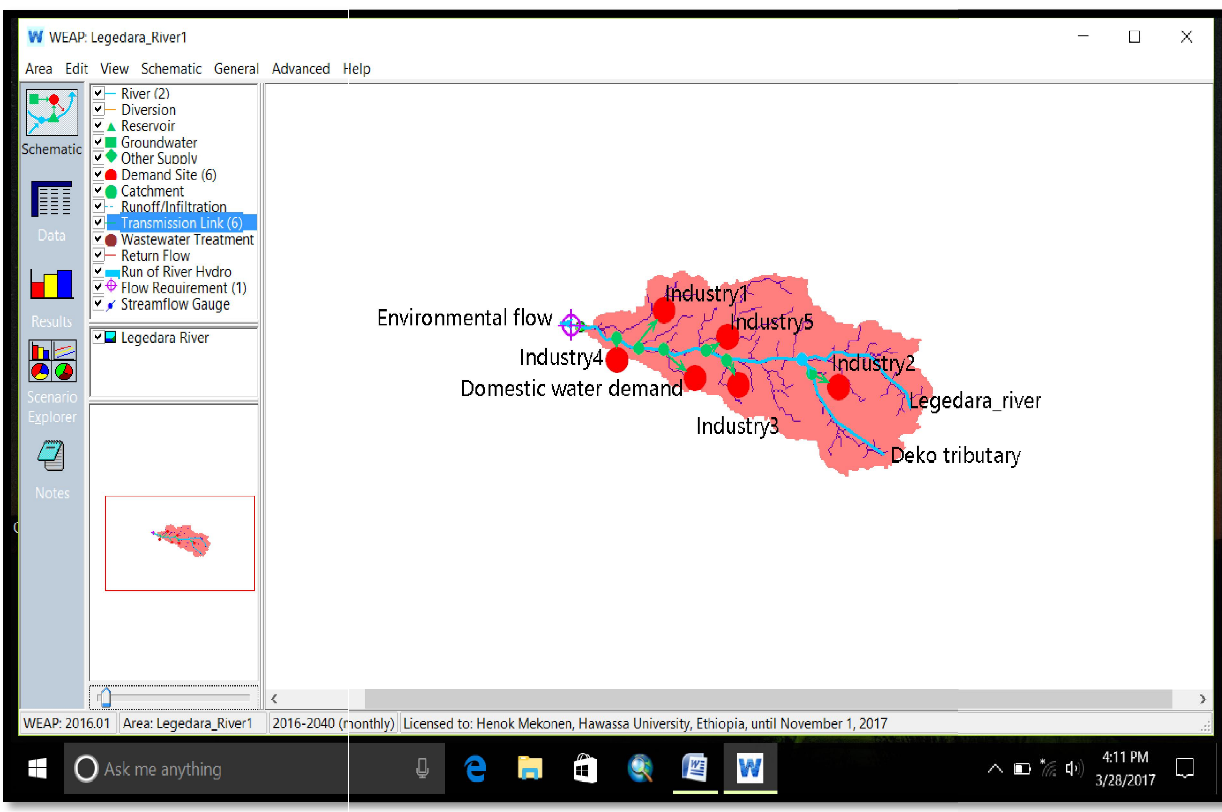

Figure 4- 15: Screenshot the schematic of Legedara river catchment of WEAP model

4.2.1. Modeling of Water Resources

Planning and allocation of water resources to different users within the catchment is one of the basic activities of water resources management to fill the gabs in water use, drought, flood protection and environmental stability (Abdullahi, 2015; SEI, 2016). This has been carried out based on water allocation to determine water demands for domestic, industrial and environmental water demand.

For present study, water users were restricted to surface water resources only. Groundwater resources of the catchment have not been considered due to lack of information on groundwater availability. The estimated runoff of Legedarariver catchment using FAO-Rainfall-Runoff model wasrepresent the available surface water resources of the Legedara river catchment. Therefore, this available water was allocated to the water users in order to solve the water allocation problem and understand the potential of water relation with the water demand within the catchment.Hence, the estimated runoff of the catchment has been used as a river flow, as suggested by Mugatsia(2010); Singh *et al*.(2014 and 2016); SEI (2016).

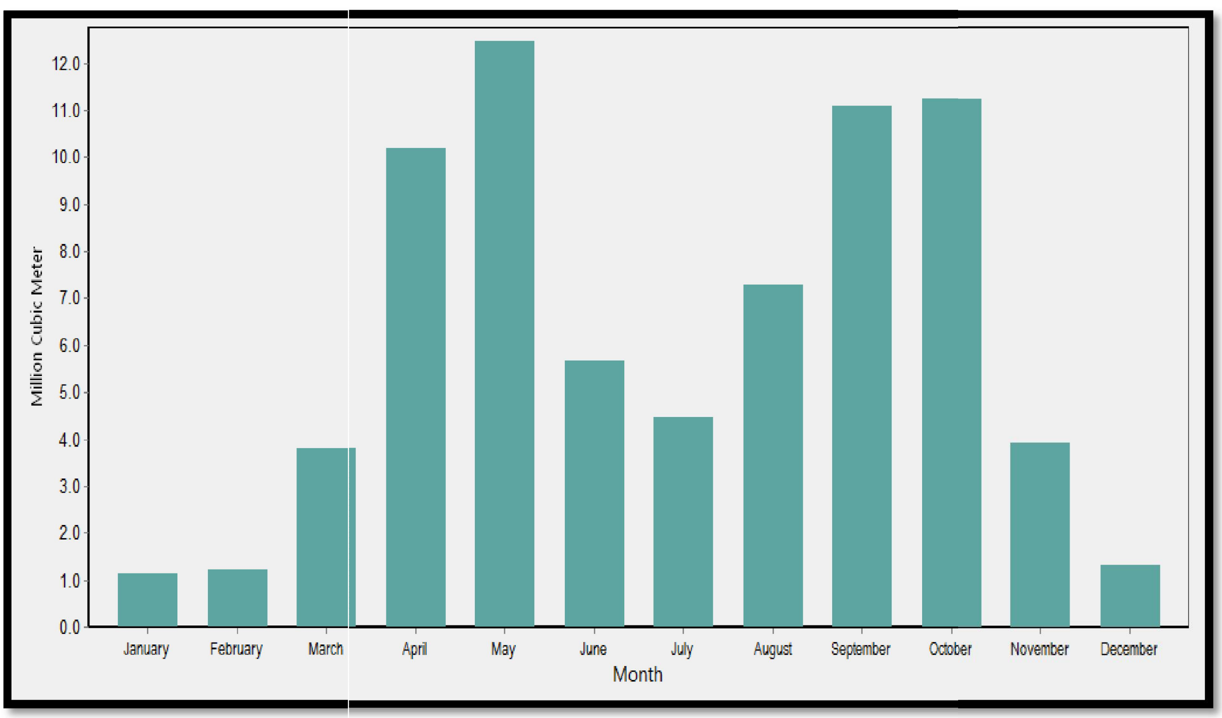

Figure 4- 16: Mean monthly runoff of Legedara river catchment (1997-2013)

Figure 4.16 show the trends of runoff of Legedarariver catchment on monthly average in order to understand the runoff of the catchment changes from month to month.As observed from Figure 4.16, during the months of January, February and December the runoff of the catchment are lower, whereas in April, May, September and October are higher.The water yield for the intermediate values of (March, June, July, August and November) months estimatedas 25.15 MCM, wet months (April, May, September and October) as 44.98MCM and dry months (January, February and December) as 3.7MCM.Therefore, the mean annual stream flow of Legedara river catchment as per WEAP model is estimated as 73.83MCM.

4.2.2. Modeling Current Situation of Domestic and Industrial Water Demand

Evaluation of the amount of water resources and demands are primary tasks in designing any water supply systems. The WEAP model needs the annual activity levels, annual water use rates of different demand sites in addition to the simulated runoff of the catchment to allocate the water for demand sites. Having all these and other inputs, the WEAP model was successful to allocate the water for the selected demand sites. The model was intended to analyze the water demand, unmet demand and different future scenarios.

Thecurrent situation (2013-2016)of water demands for the selected water users were modeled before any scenario development in order to know the current situation of water resources and demands of the catchment. Therefore, the water demands were restricted on domestic, industrial and environmental demand, while irrigation water demand was not included due to limitation of information about the potential irrigable area within the catchment.

There is one major urban area which has been deriving water from Legedara river catchment for domestic use. Therefore for present study, Dilla town was considered for modeling of domestic water use. Therefore, the projected population from 2013-2016 wasobtained from CSA of Ethiopia. This projected population was used to determine the current situation of domestic water demand.

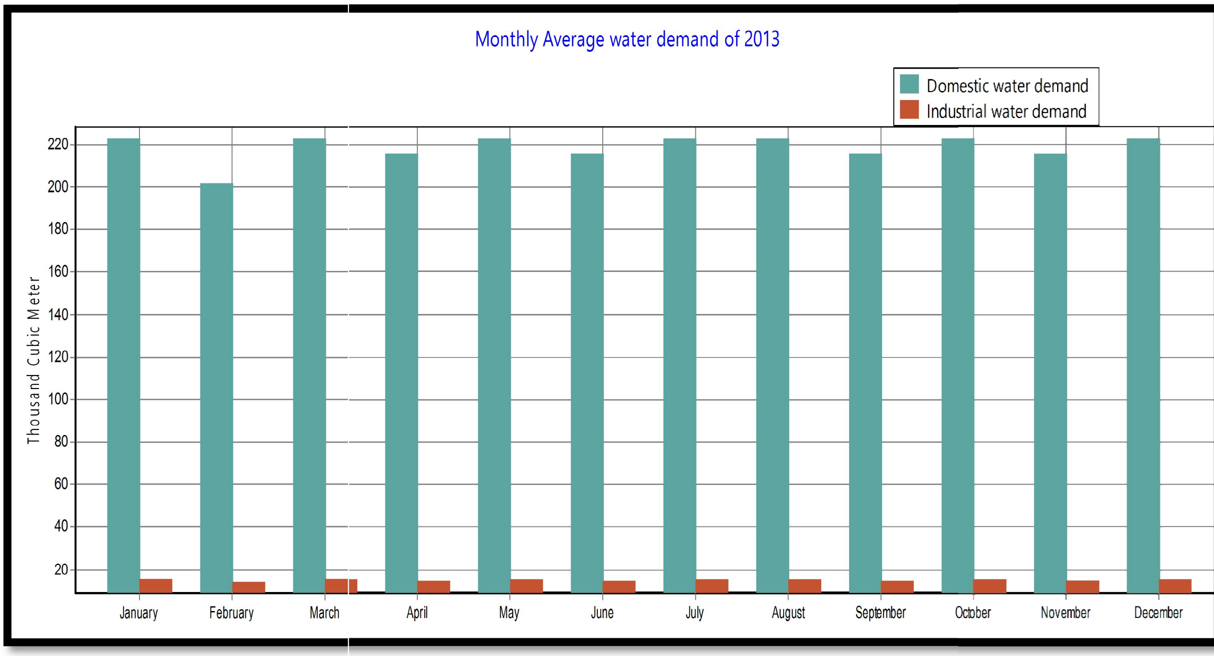

Figure 4- 17: Average monthly water demand of 2013

As Figure 4.17 indicates that domestic water demand is the major water user in the catchment. The base year annual domestic water demand is estimated to be 2.63MCM while industrial water demand is 0.18MCM. Therefore, the base year water demand excluding environmental flow requirement are 2.81MCM.

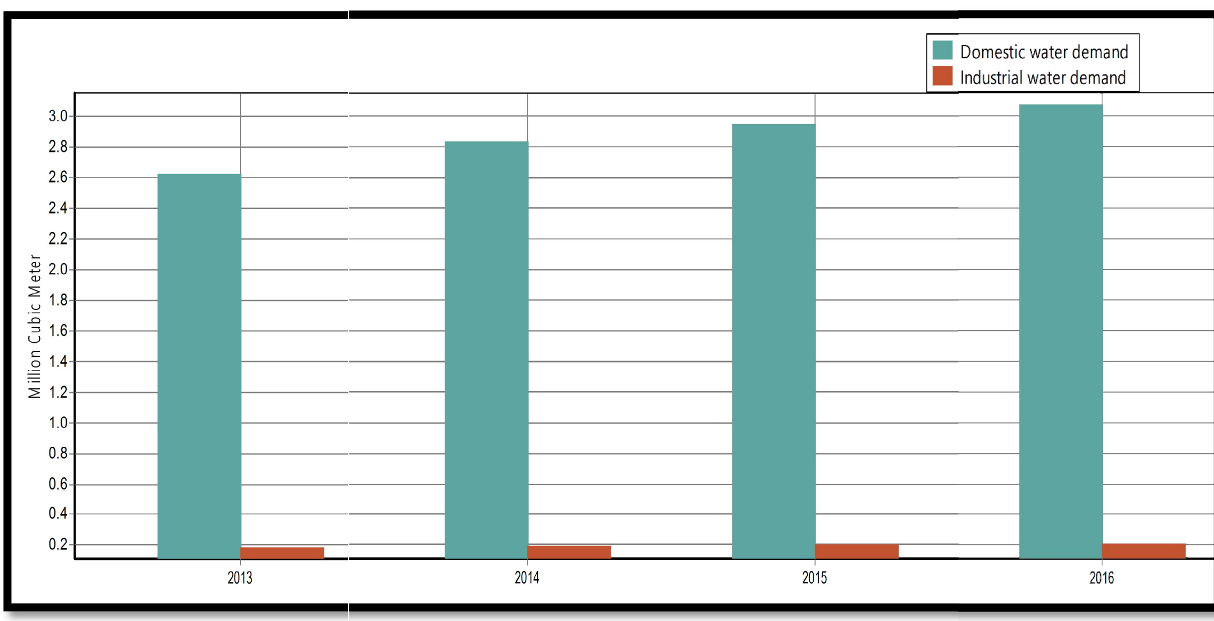

Figure 4- 18: Annual water demand of the current situation (2013-2016)

Figure 4.18 shows that, at the end of the current situation (2016) annual domestic water demand is estimated to be 3.08MCM while industrial water demand is 0.21MCM. Therefore, the current situation water demand excluding environmental flow requirement are 3.29MCM.

4.2.3. Environmental Flow Requirement

The flow duration curve is used to derive specific flow percentiles (percentage exceedence values) associated with required suitable river conditions, often in combination with a professional judgment, to produce environmental flow requirements (Jakia, 2011; Abdullahi, 2015; SEI, 2016). Flow duration curve shows the percentage of the time that certain values of discharge were equaled or exceeded in the available number of years of record.A basic flow duration curve measures high flows to low flows along the x-axis represents the percentages of time (frequency of occurrence) that a particular flow is equaled or exceeded. The Y- axis represents the quantity of flow at a given time steps, associated with a duration. Flow duration intervals are expressed a percentage of exceedance, with zero corresponding to the highest stream discharge (i.e. flood conditions) and 100 to the lowest (i.e. drought conditions).

Jakia (2011) suggested that the sustained flow of a river is considered at a target of 90% of flow duration curve used to sustain environmental flows. However, in this study, a target of 80%of flow duration curve was used to sustain environmental flows and also by considering livestock water demand and Gidabo dam. Therefore, 20% of the total flows were allocated as environmental flow requirement.Abdullahi (2015)suggested that FDC using WEAP model is an important tool to allocate water for environment.

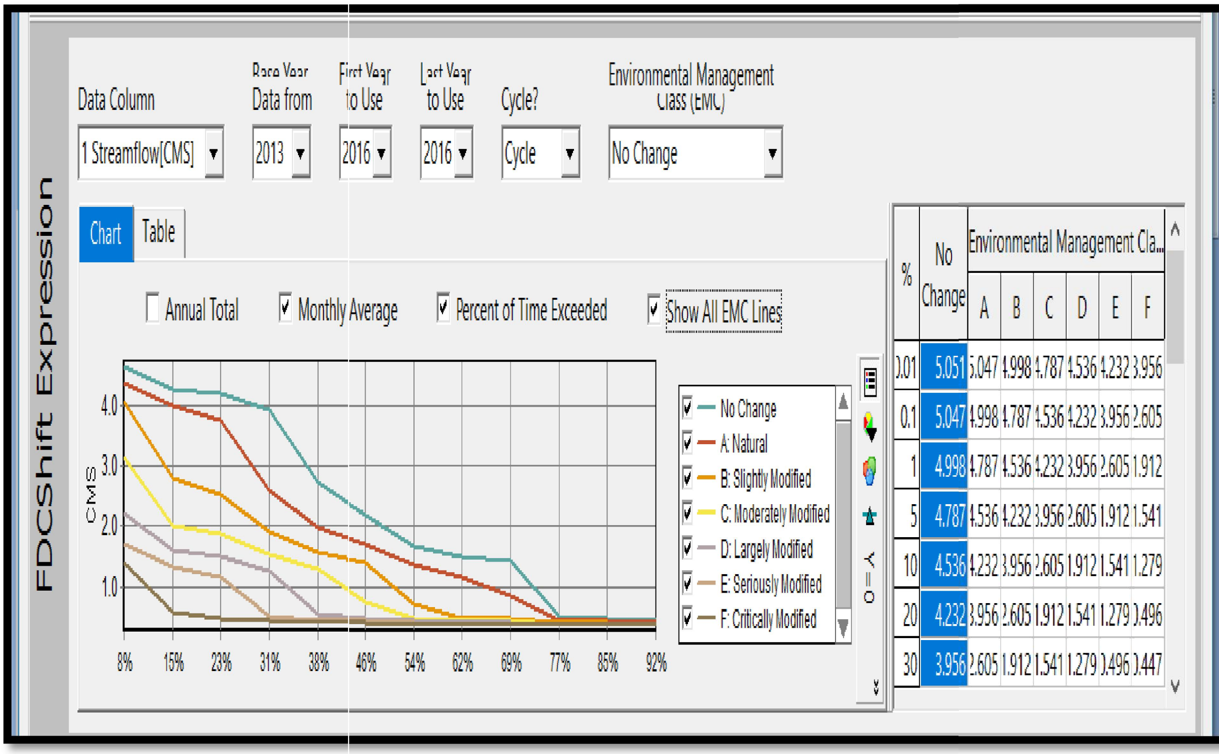

Figure 4- 19: Environmental management class of Legedara river catchment

Figure 4.19 shows that the FDC expression of different stages of environmental management class from no change to critically modified.

The monthly minimum environmental flow requirement of Legedara river catchment was depicted on Figure 4.20.The chart shows that the minimum environmental flow requirement varies in a similar trend with the mean monthly stream flow.The base year an annual environmental flow requirement is estimated to be 14.77MCM.

Alemayehu*et al.*(2010);Abdullahi(2015); Tena*et al.* (2016); Shumet and Mengistu (2016) witnessed that allocation of water for environmental flow requirementis based on the trends of the stream flows.

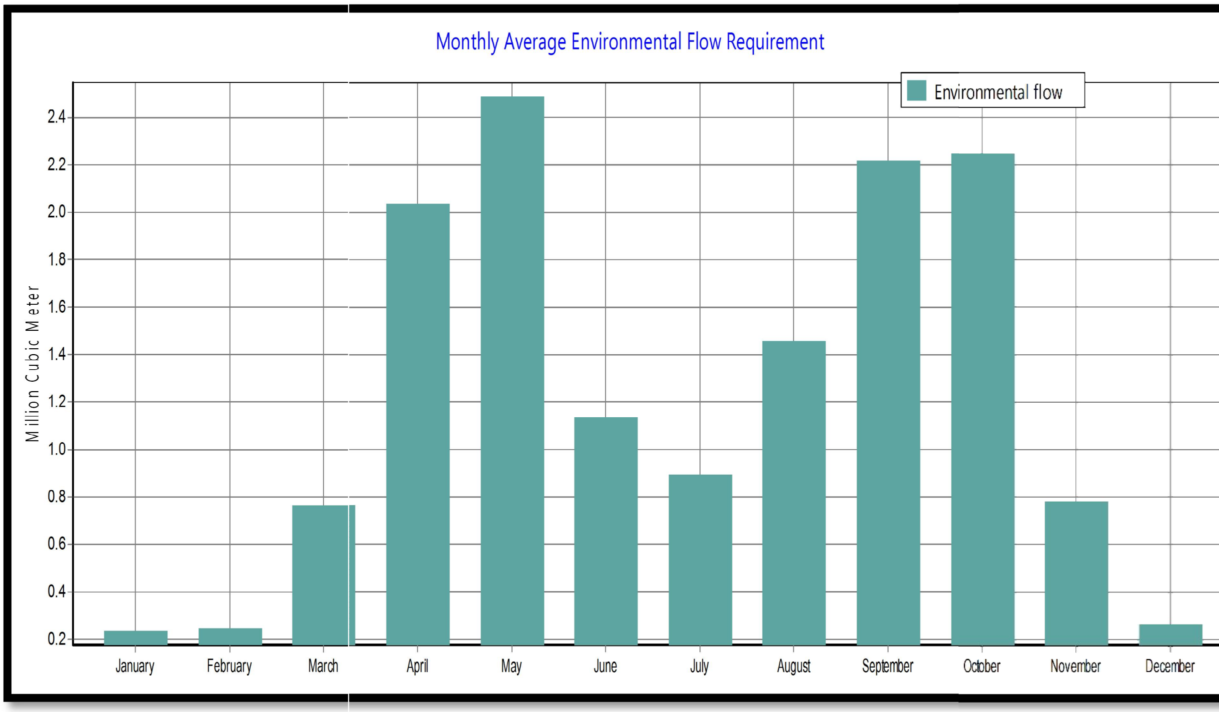

Figure 4- 20: Environmental flow requirement

The output of WEAP model shows that at the end of current situation (2016) the mean annual flow has been decreased to 55.77MCM. This shows that the water consumed by demand sites including environmental flow requirement is to be 18.06MCM (24.46% of the total annual stream flow). The results are depicted on Figure 2.21. During the current situation, no unmet demands were occurred;even the months of January, February and December are the lowest available water resources. Hence,all the selected demand sites have been satisfied.

NB: Unmet demand is the amount of each demand site's requirement that is not met.

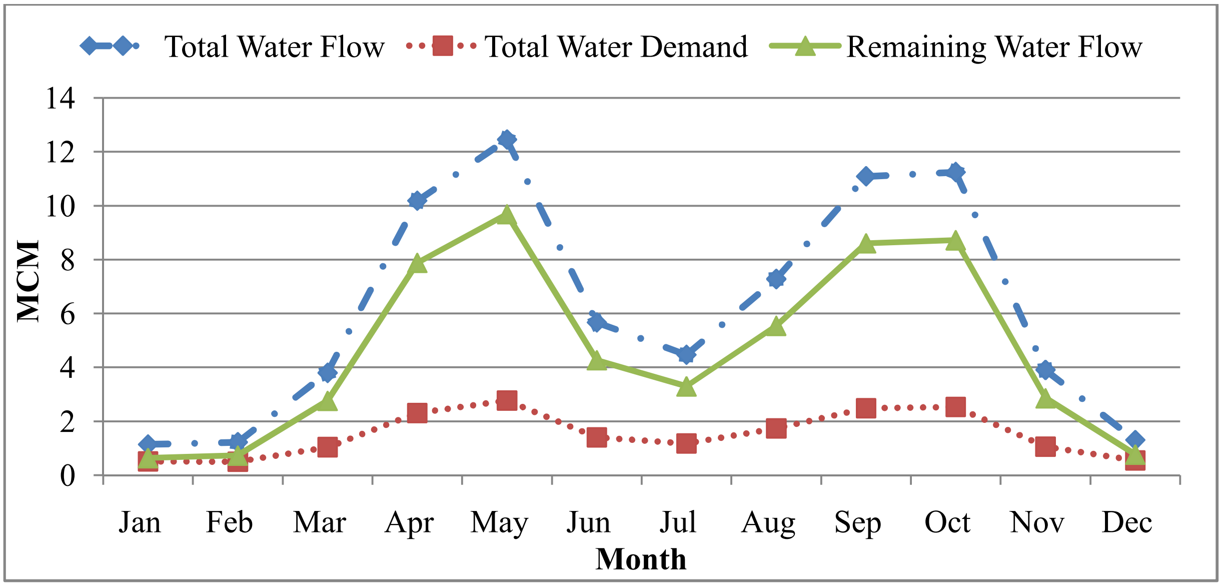

Figure 4- 21: Comparison of water resources and demands for the current situation

4.3. ScenariosAnalysis

At the heart of WEAP is the concept of scenario analysis. Using WEAP model a scenario can be built and compared to assess their water requirement, cost and environmental impacts (Abdullahi, 2015; SEI, 2016).Selected future development scenarios were modeled to evaluate water resources availability with respect to the water demand of the user sectors.Therefore for present study, six scenarios including reference scenario were developed and evaluated based on the availability of data. See Appendix Figure 7.14 about the development of scenarios by WEAP model.

4.3.1. Reference Scenario(2017-2040)

Reference scenario represents the changes that are likely to occur in the future without interventions or new policy measures. It is also business-as-usual scenario. Finally, "what if" scenarios can be developed to alter the reference scenario and evaluate the effects of changes in policy and technologies (Yates *et al*., 2005; Mugatsia, 2010; Abdullahi, 2015; SEI, 2016).

In this scenario, no changes were made except the incremental of population with an annual growth rate of 4% as recommended by CSA of Ethiopia. The projected population is depicted on Appendix Figure 7.7. Therefore, the industrial water demand is 7% of domestic water demand, the annual water use rate of domestic water is 25.55m^3/year/capita, and environmental flow requirement also assumed constant. In other words, no any interventions and policy changes were made from current situation. Hence, the results were depicted on Figure 4.22

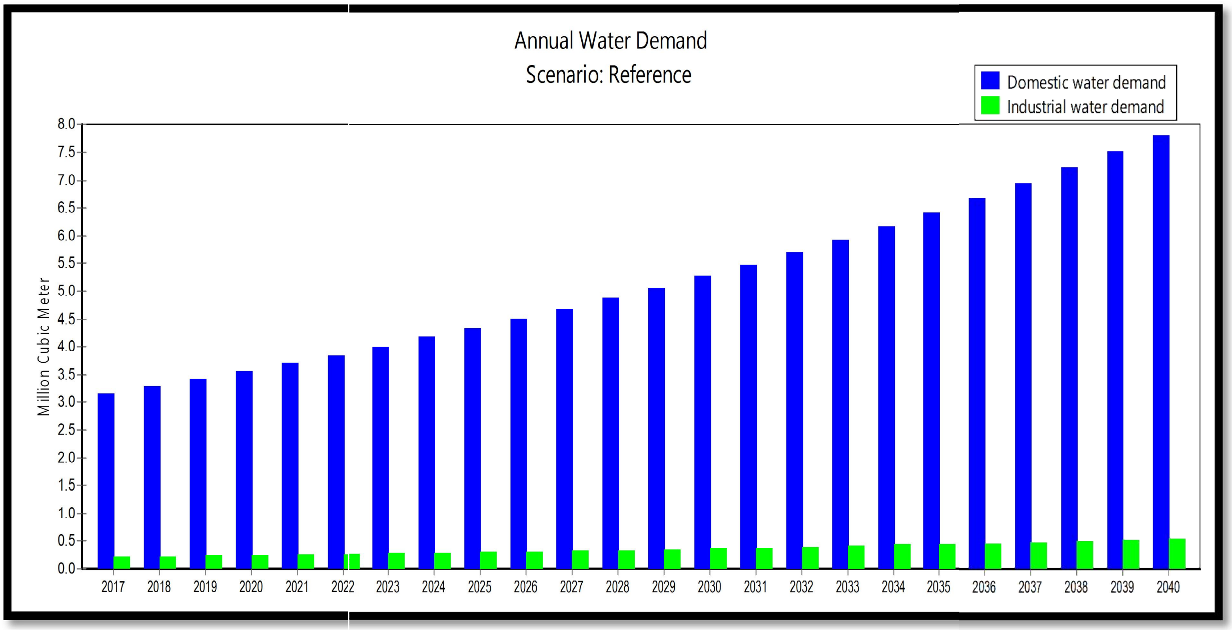

Figure 4- 22: Annual water demand of reference scenario (2017-2040)

Figure 4.22 shows the annual total water demand in 2017until the last year scenario in 2040 for two demand sites. So, the water demands change with the increase of the population number. The annual water demands in 2017 excluding environmental flow requirements is estimated to be 3.39MCM while in 2040 is 8.36MCM.The increment of water demand is clearly due to the population growth.

Figure 4.23 portrays that, at the end of the reference scenario (2040) the water demands including environmental flow requirement will be 23.12MCM (31.3% of total annual flow) and the remaining water that will not used is 50.71MCM and will be available in the system for further development with care implementation. Under these situations the available water resources in the area is sufficient for some careful implementation of projects except during dry seasons. As a result, during the reference scenarioall the selected demand sites were satisfied, even in the month of January, February and December, because in this month the available water resource of the catchment is lower compared to other months. Therefore,unmet demands were not occurred in reference scenario.

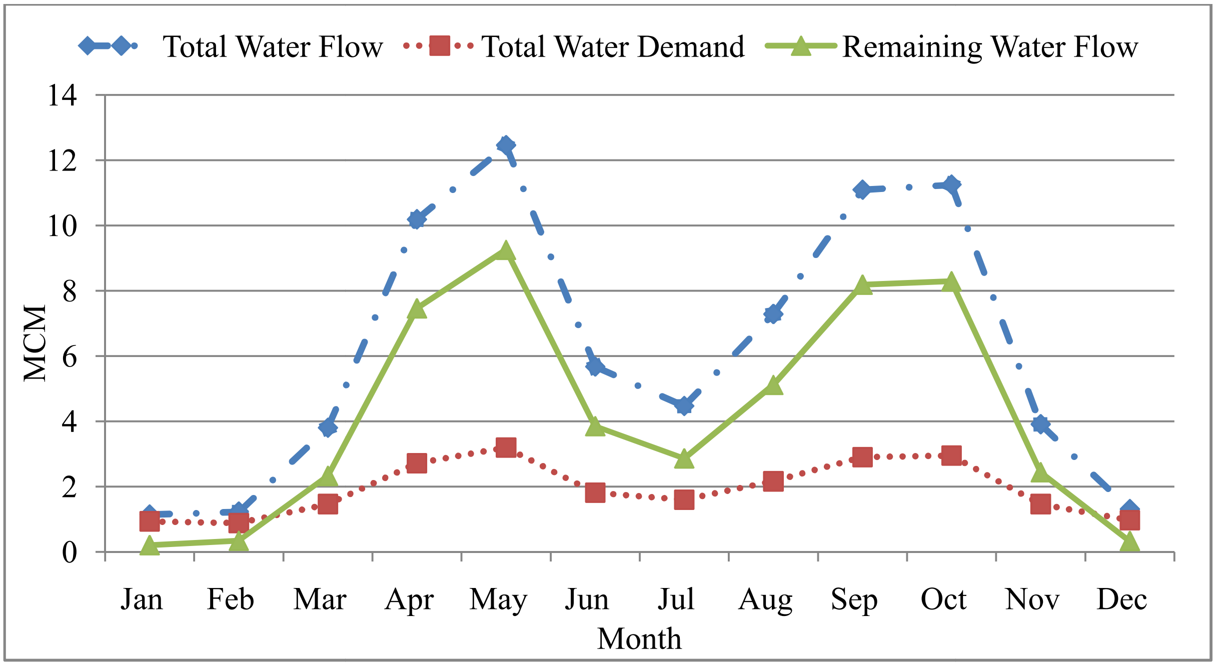

Figure 4- 23: Comparison of water resources and demands at the end of reference scenario (2040)

4.3.2. Scenario One: High Population Growth Rate(2017-2040)

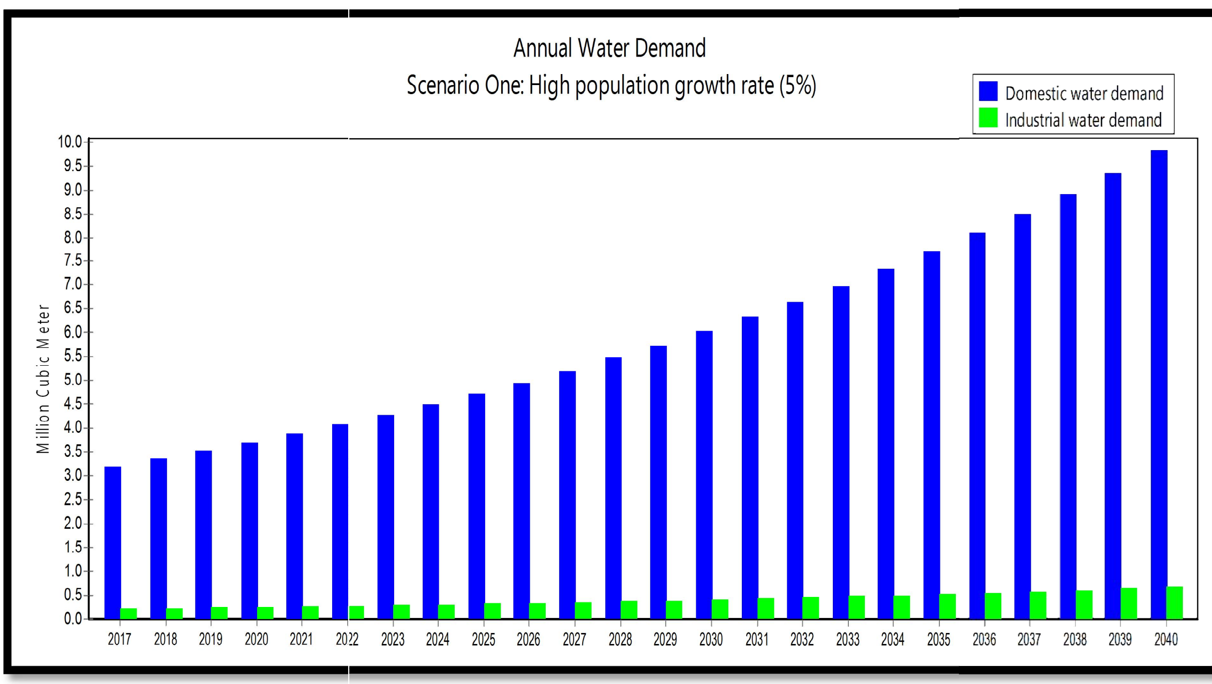

Figure 4- 24: Annual water demand of scenario One(2017-2040)

Figure 4.24shows the total annual water demands in 2017until the last year scenario in 2040for two demand sites. As observed form Appendix Figure 4.8, the population number increase linearly in the future. So, the water demandincreases with the increase of the population number. The annual water demands in 2017 excluding environmental flow requirement is estimated to be 3.44MCM while in 2040is 10.55MCM. As can be observed in Figure 4.24, at the end of scenario one (2040) the annual domestic water demand is estimated to be 9.86MCM while industrial water demand is 0.69MCM. The domestic and industrial water demand increased to higher level of increment than the reference scenario water demand showed. The result shows that there will be an increment in water demands from 8.36MCM to 10.55MCM (excluding environmental flow requirement) in the year 2040 in reference to the reference scenario of 2040. This implies that,there is an increment by 26.2% in the year 2040 in high population growth rate scenario with respect to reference scenario. The increment isdue to the population growth rate change from 4% to 5%.

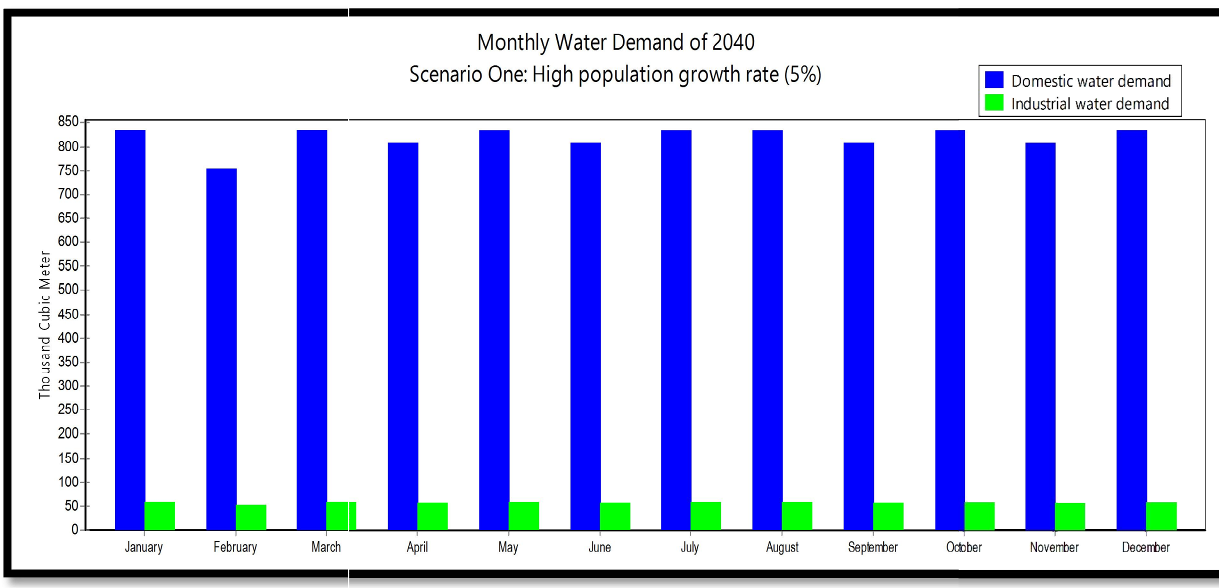

Figure 4- 25: Monthly water demand at the end of scenario one (2040)

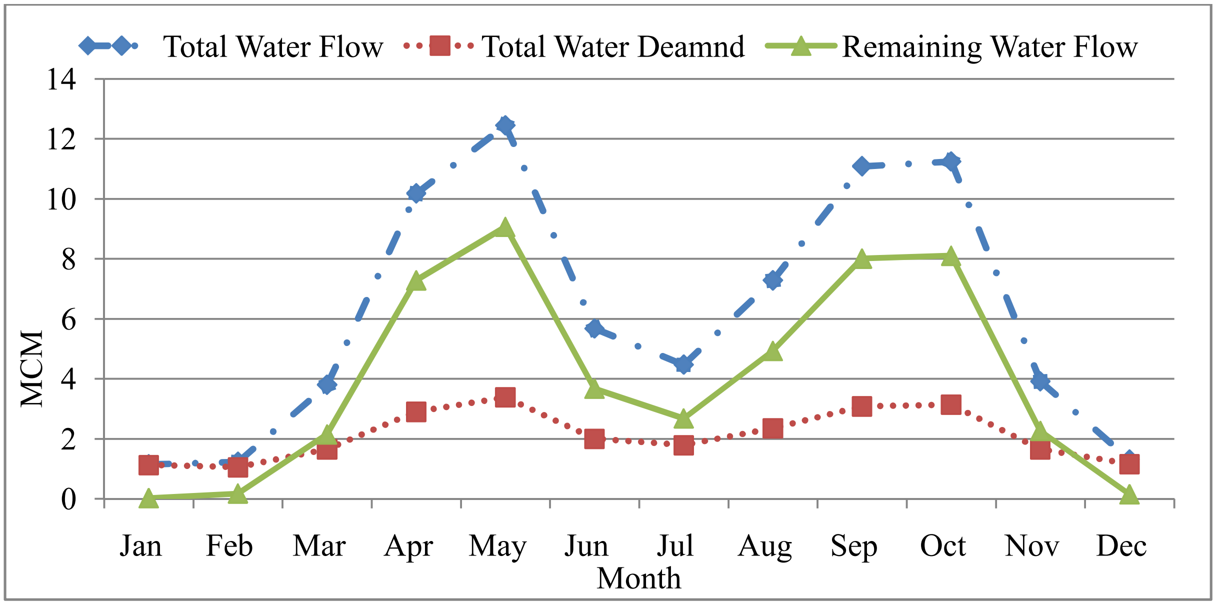

Figure 4- 26: Comparison of water resources and demands at the end of scenario one (2040)

Figure 4.26 demonstrates thatat the end of scenario one (2040) the mean annual flow will bedecrease from 73.83MCM to 48.55MCM.This shows that the water consumed by demand sites including environmental flow requirement is estimated to be 25.28MCM (34.24% of total annual flow). Therefore, all sectoral water demands have been meet and no unmet demand were occurred in scenario one, even the months of January, February and December are the lowest available water resources.

4.3.3. Scenario Two: Low Population Growth Rate (2017-2040)

Annual domestic water demand with an annual growth rate of 3% was used in this scenario whereas other variables were assumed that to be constant. Therefore, based on the above defined assumptions the catchment water demandsrelations to the available water resources of the Legedara river catchment were evaluated. The result of this scenario was depicted on Figure 4.27.

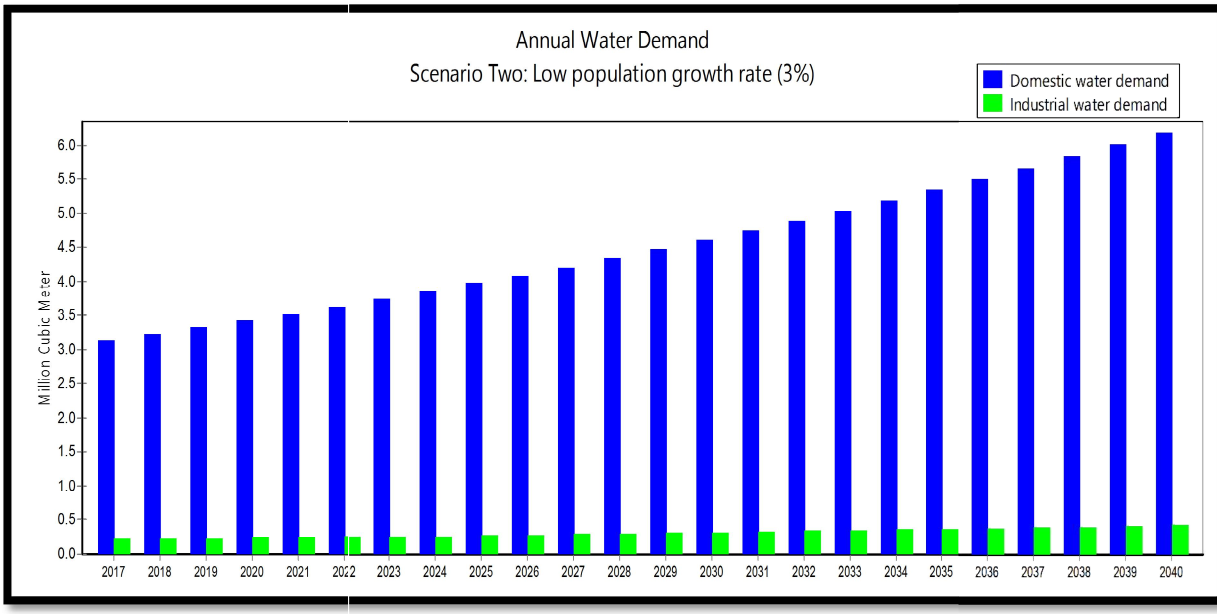

Figure 4- 27: Annual water demand of scenario two (2017-2040)

As illustrated in Figure 4.27, the annual total water demand in 2017 until the last year scenario in 2040 for two demand sites were increased.The annual water demands in 2017 excluding environmental flow requirement is estimated to be 3.35MCM while in 2040 is 6.62MCM.At the end of scenario two (2040), the annual domestic water demand is estimated to be 6.19MCM while industrial water demand is 0.43MCM.This result found that the annual water demands will be reduce by 20.81% in the year 2040 in scenario two with respect to the reference scenario. This is clearly due to the declining of population growth rate.

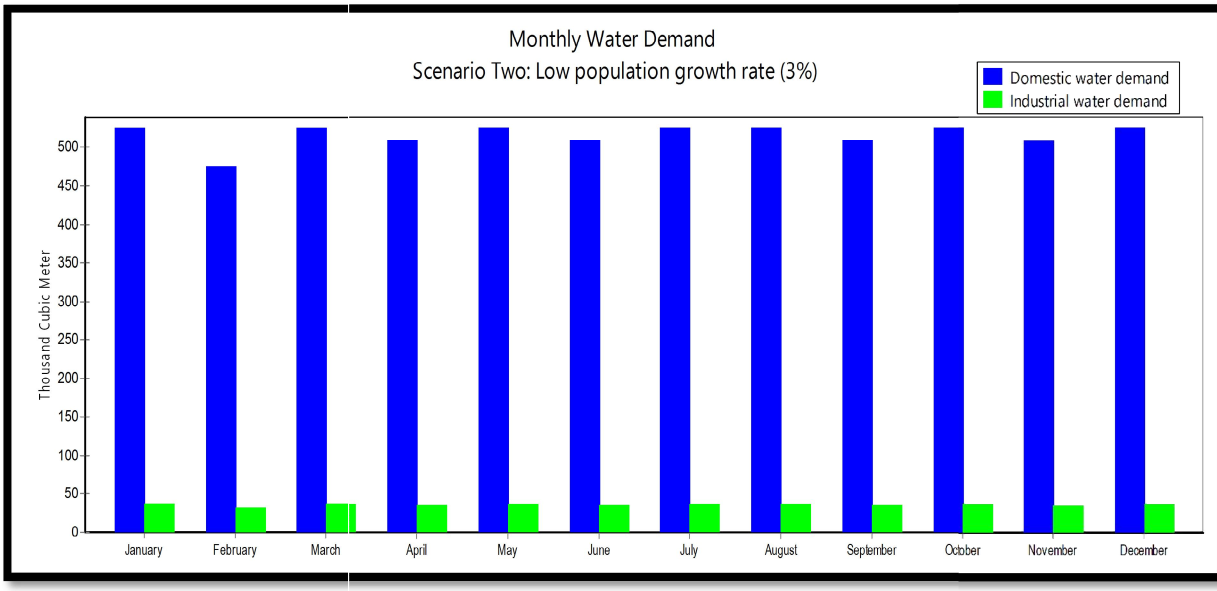

Figure 4- 28: Monthly water demand at the end of scenario two(2040)

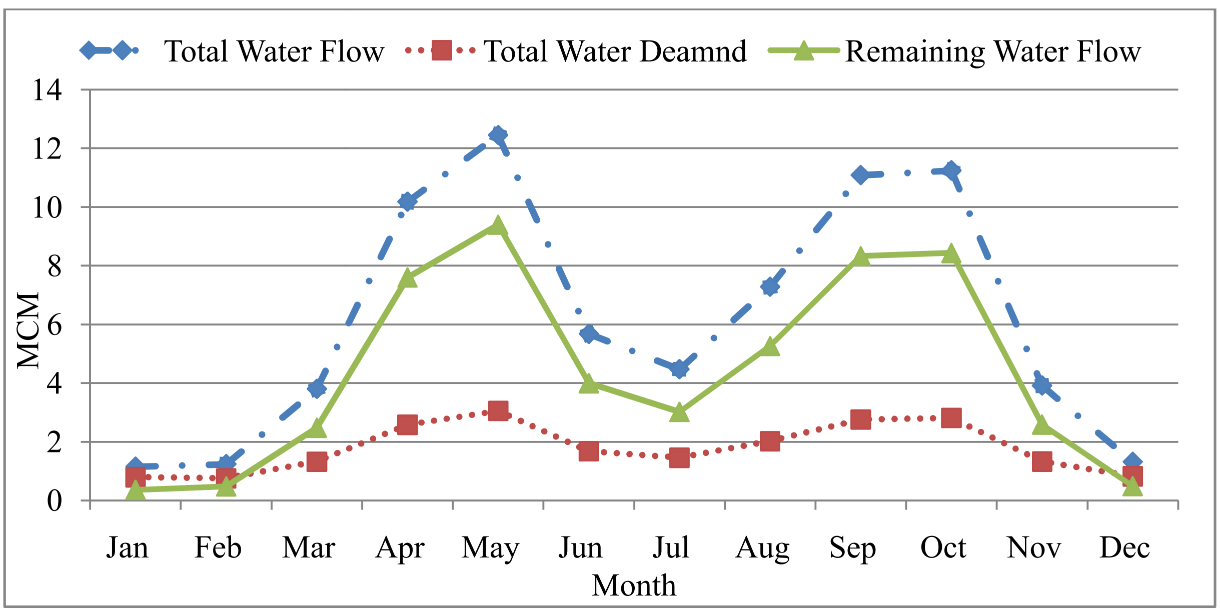

Figure 4- 29: Comparison of water resources and demands at the end of scenario two (2040)

As observed from Figure 4.29, at the end of scenario two (2040) the mean annual flow will bedecrease from 73.83MCM to 52.44MCM.This shows that the water consumed by demand sites including environmental flow requirement is to be 21.39MCM (28.97% of total annual flow). Therefore, all sectoral water demands have been meet. Hence, no unmet demands were occurred in scenario two, even the months of January, February and December are the lowest available water resources.

4.3.4. Scenario Three: High Annual Water Use Rate (2017-2040)

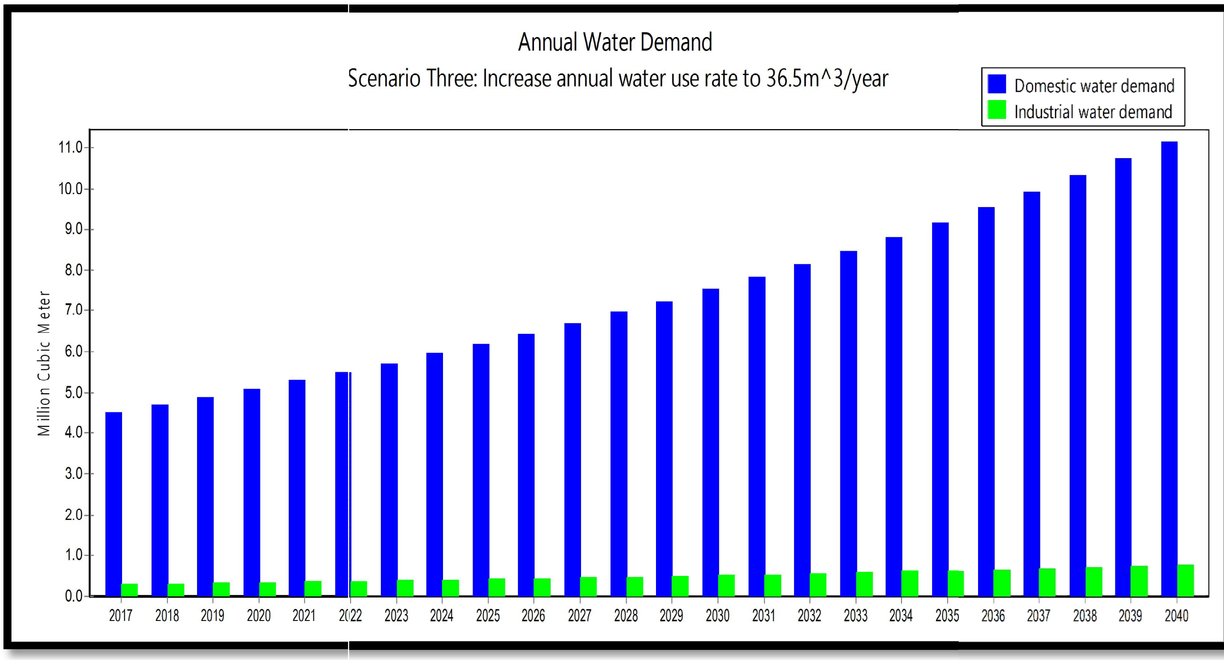

Figure 4- 30: Annual water demand of scenario three

As can be observed in Figure 4.30, the annual total water demand in 2017 until the last year scenario in 2040 for two demand sites were increased. The annual water demand in 2017 excluding environmental flow requirement is estimated to be 4.85MCM while in 2040 is11.94MCM. This result showed that there will be an increment in water demand from 8.36 MCM to 11.94MCM (excluding environmental flow requirement) scenario three (2040) in reference to the reference scenario (2040). There is an increment by 42.82%. This is clearly due to the increment of annual water use rate from 25.55m^3/year/capita to 36.5m^3/year/capita.At the end of scenario three (2040), the annual domestic water demand is estimated to be 11.16MCM while industrial water demand is 0.78MCM.

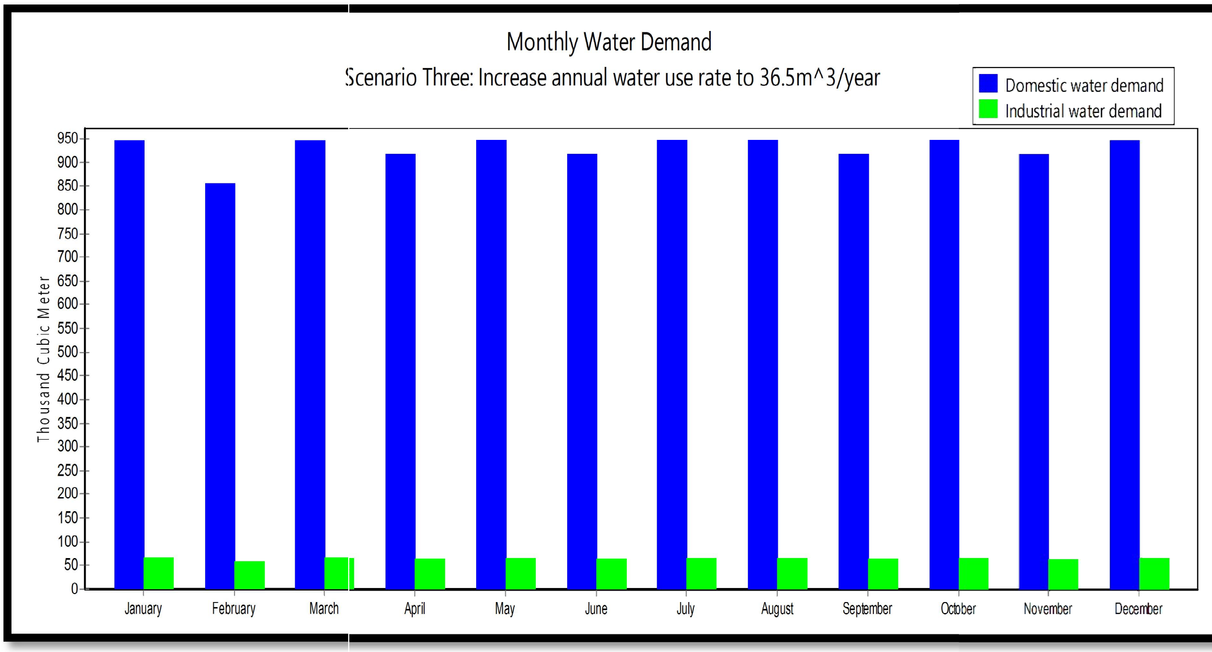

Figure 4- 31: Monthly water demand at the end of scenario three (2040)

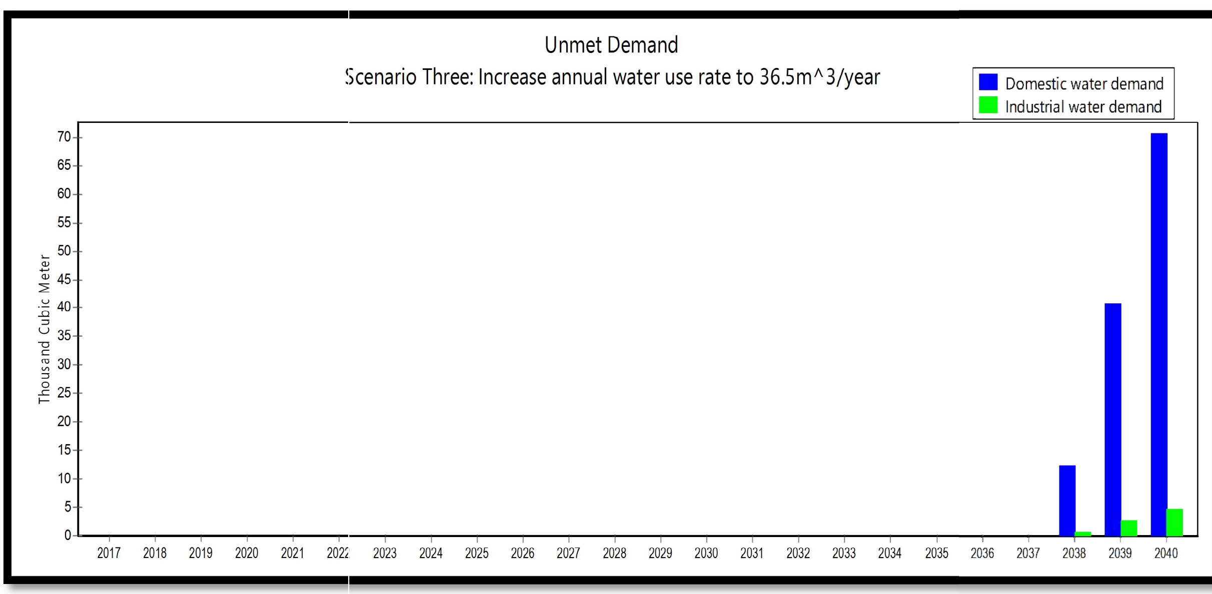

Figure 4- 32: unmet demand of scenario three

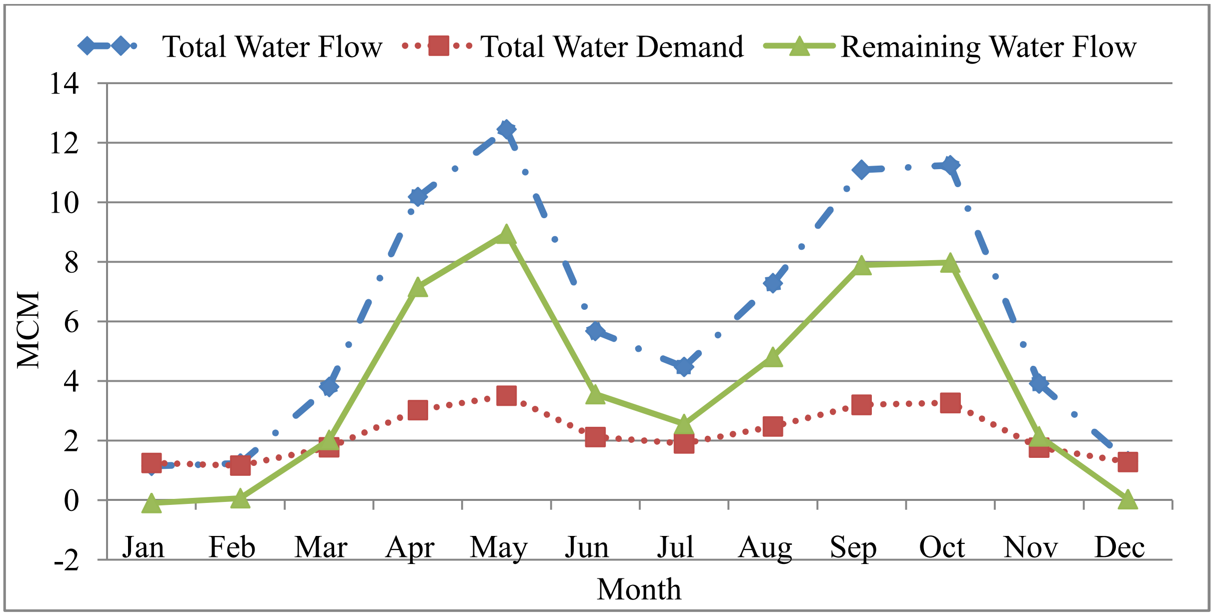

Figure 4- 33: Comparison of water resources and demands at the end of scenario three (2040)

The output of WEAP model shows that at the end of scenario three (2040) the mean annual flow will be decrease from 73.83MCM to 47.12MCM.This confirms that the water consumed by demand sites including environmental flow requirement is to be 26.71MCM (36.17% of total annual flow). As illustrated in Figure 4.32 and 4.33, during scenario three, the water demands of domestic and industrial demand sites were not fully satisfied. The annual unmet demand at the end of scenario three would reach about $75.77\times10^{3}m^{3}$. Hence, unmet demands were occurred in the months of January, because in this month the available water resource of the catchment is lower compared to the water demands, while in the other months the availability is efficient and all users have 100% coverage. The overall annual unmet demand in scenario three is found to be 0.28%. This implies the overall coverage of water demand is 99.72%.Nevertheless, the output of WEAP model shows that environmental flow requirement of 14.76MCM will be fully delivered at the outlet of Legedara river catchment. Hence, no absolute scarcity of water would develop.

4.3.5. Scenario Four: Low Annual Water Use Rate (2017-2040)

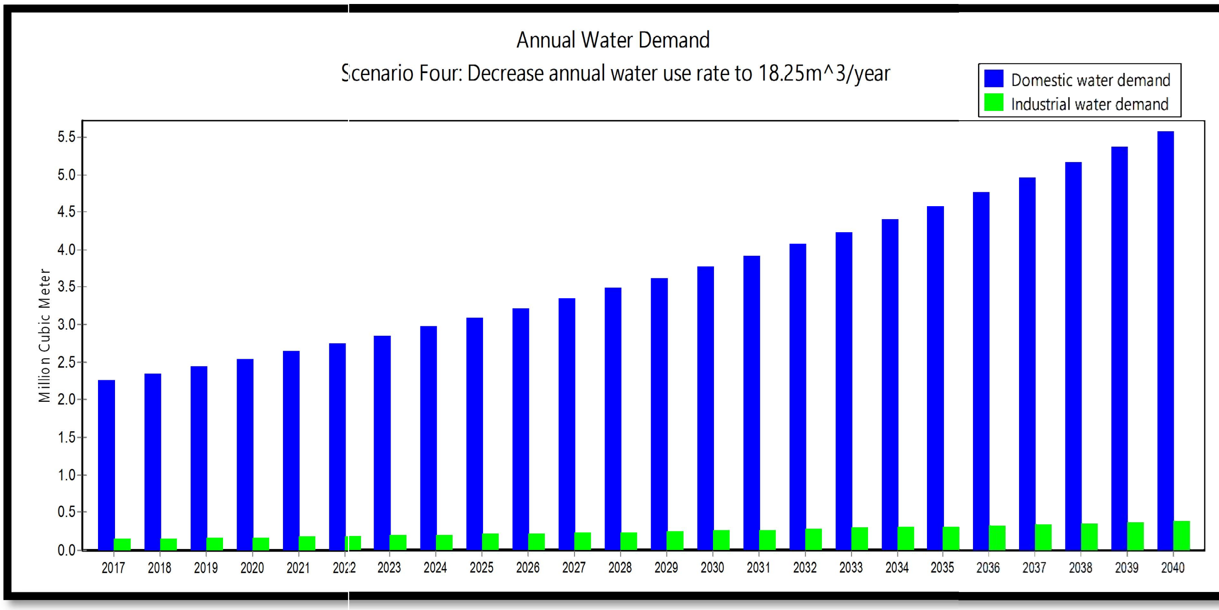

Figure 4- 34: Annual water demand of scenario four

The annual water demand in 2017 excluding environmental flow requirementsis estimated to be 2.42MCM while in 2040 is 5.97MCM in scenario four. This result shows that there will be a decline in water demand from 8.36 MCM to 5.97MCM (excluding environmental flow requirement) scenario four (2040) in reference to the reference scenario (2040). The reduction is by 28.6%. This is clearly due to the decline of annual water use rate from 25.55m^3/ year/capita to 18.25m^3/year/capita.As shown in Figure 4.34 and 4.35, at the end of scenario four (2040) the annual domestic water demand is estimated to be 5.58MCM while industrial water demand is 0.39MCM.

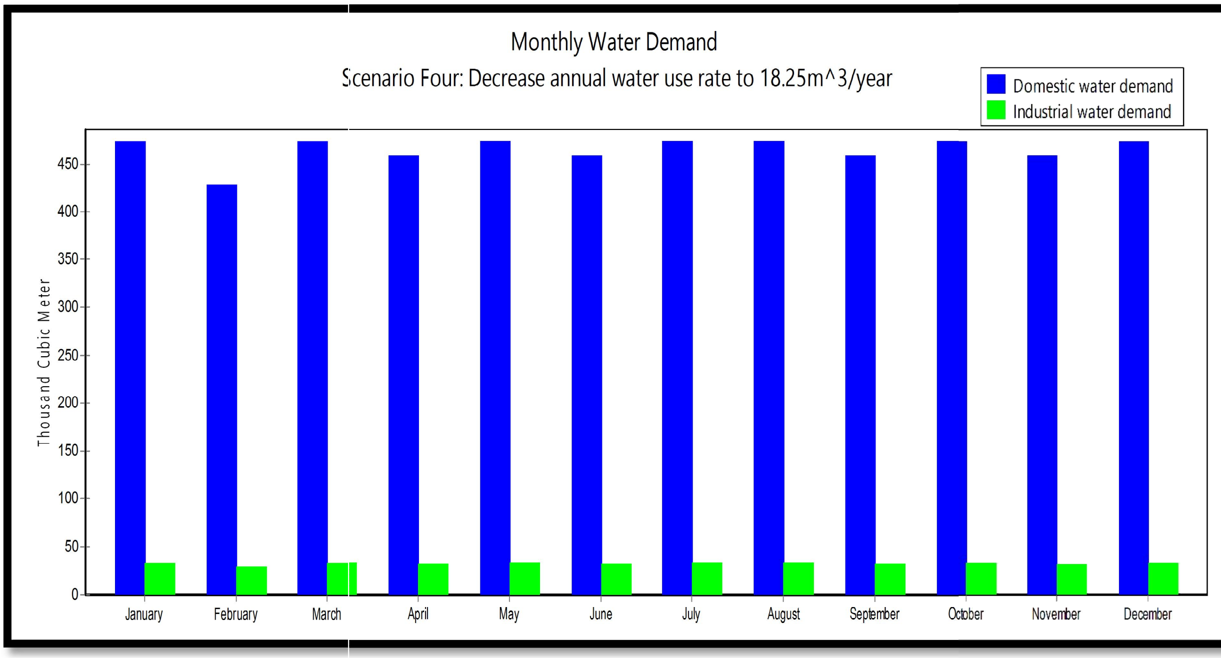

Figure 4- 35: Monthly water demand at the end of scenario four (2040)

Figure 4.36 portrays, at the end of scenario four (2040) the mean annual flow of Legedara river catchmenthas been decreased to 53.10MCM.This shows that the water consumed by demand sites including environmental flow requirement is to be 20.73MCM (28.08% of total annual flow). Therefore, all sectoral water demands have been meet. Hence, no unmet demands were occurred in scenario four.

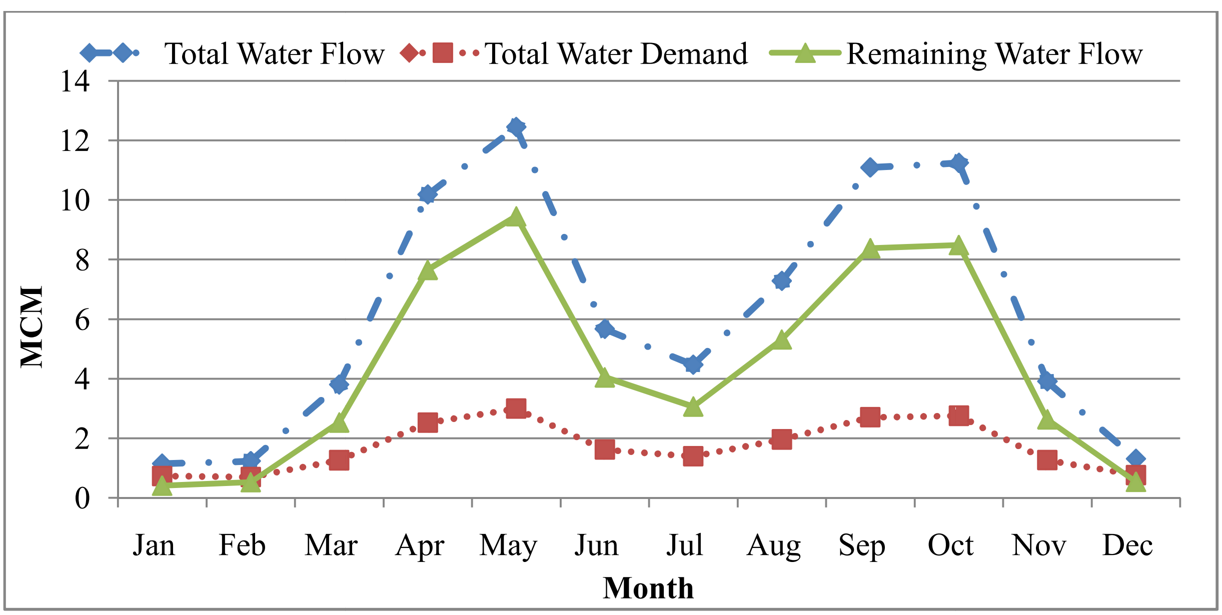

Figure 4- 36: Comparison of water resources and demands at the end of scenario four (2040)

4.3.6. Scenario Five: Raifall Change

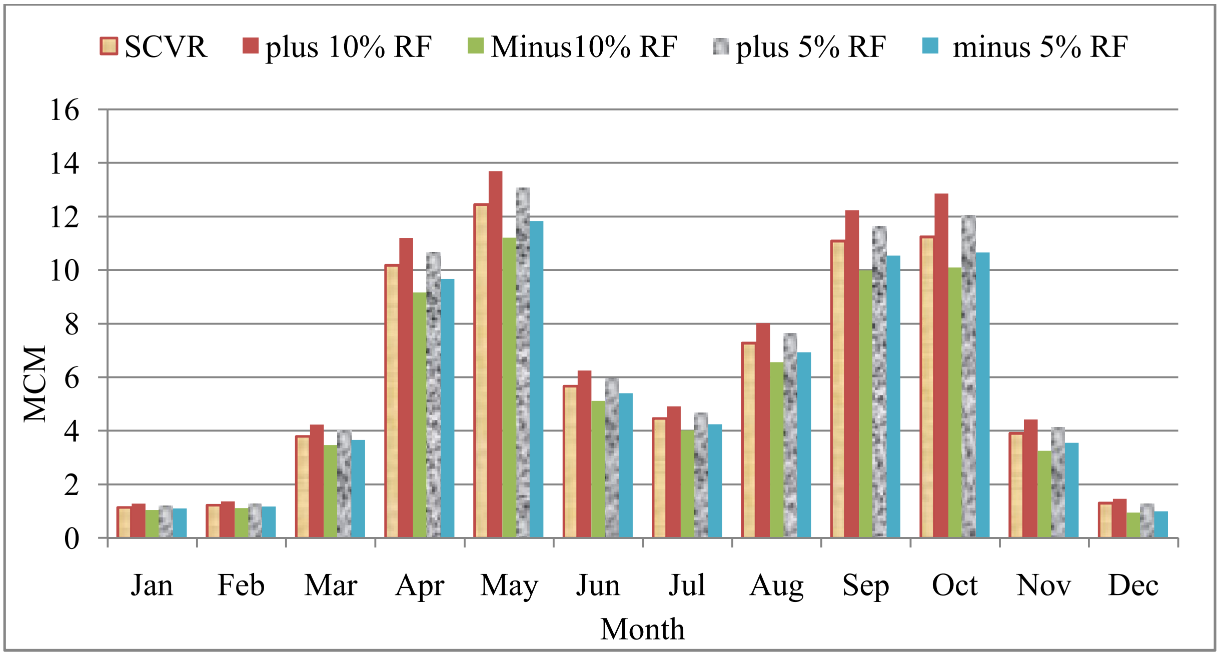

Figure 4- 37: Legedara river catchment runoff of scenario five

Where; SCVR: Simulated Current Runoff Value; Plus 10% RF: Simulated runoff when current rainfall value increasedby 10%; Minus 10% RF: Simulated runoff when current rainfall value reduced by 10%;Plus 5% RF: Simulated runoff when current rainfall value increased by 5%; minus 5% RF: Simulated runoff when current rainfall value reduced by 5%.

As illustrated in Figure 4.37, consequently the model output revealed that upon increase and decrease of current mean monthly rainfall by 10% the mean annual catchment runoff has been increased or decreased from current value by up to 8.09MCM (10.95%) and 7.86MCM (10.64%) respectively, while by increasing or decreasing 5% catchment runoff has been increased or decreased by 4.09MCM (5.54%)and 3.93MCM (5.3%)from the actual value. Therefore the changes in rainfall have considerable impact on increase or decrease of catchment runoff.

Table 4- 5: Summary of annual change of river flow at the end of each scenario (MCM)

No.	Output of WEAP model (natural flow)	Reference	Scenario one	Scenario two	Scenario three	Scenario four
Legedara river	73.83	50.71	48.55	52.44	47.12	53.10

Table 4- 6: Summary of annual total water demand at the end of each scenario (MCM)

No.	Reference	Scenario one	Scenario two	Scenario three	Scenario four
Water demand	23.12	25.28	21.39	26.71	20.73

Table 4- 7: Summary of monthly total unmet demand at the end of each scenario (Thousands of m3)

Month	January	February	December
Reference scenario	0	0	0
Scenario one	0	0	0
Scenario two	0	0	0
Scenario three	75.77	0	0
Scenario four	0	0	0

5. CONCLUSIONS AND RECOMMENDATIONS

1.1. Conclusions

The comprehensive understanding of hydrological process in the catchment is the pre-requisite for successful of water resources management and environmental restoration. In this study, WEAP model was used to estimate the water resources and demands of Legedara river catchment for effective water management through scenario analysis.

As a result of parameter derivation hydro-meteorological gauged Waleme river catchment is almost found similar with ungaugedLegedara river catchment.Therefore, model calibration and validation were performed to assess the model performance. The results were found satisfactory for the gauged Waleme river catchment (ENS = 0.81, R^2 = 0.86 and RVE = -2.64 for calibration and ENS = 0.77, R^2 = 0.83 and RVE = -7.73 for validation). Following calibration and validation of gauged catchment, runoff of Legedara river catchment was simulated.

According to the water balance estimated using FAO-Rainfall-Runoff model, the hydrological water balance components that play an important role in the catchment are rainfall, reference evapotranspiration, actual evapotranspiration, and runoff with 1316.42mm, 1142.07mm, 538.78mm and 778.65mm respectively.

The mean annual flow of Legedara river catchment was observed to be 73.83MCM, while the monthly average based on the simulated flow from 1997-2013 indicates that January, February and December are the lowest months of available water resources in the catchment. As observed from this research, Legedara river catchment has capability to fulfill all the selected demand sites, while only in scenario threethere will be unmet demand in the month of January.The water demand including environmental flow requirement in the current situation of the year 2016 is 18.06MCM,whereas this demand grows to 23.12MCM, 25.28MCM, 21.39MCM, 26.71MCM and 20.13MCM in reference scenario, scenario one, two, three and four of the year 2040 respectively. The result of WEAP model shows that the water demand is increasing in the future due to fast growing population and high annual water use rate.In scenario five, the result demonstrated that increase and decrease of current mean monthly rainfall values by 10% and 5%have an impact on increase or decrease of catchment runoff by 10.95%, 10.64%, 5.54% and 5.3% respectively.

Despite the uncertainties and constraints concerning the model, input data, this study shows that WEAP model offer reasonable results to assist stakeholders in developing recommendations for improved water management.

1.2. Recommendations

Based on the study conducted the following recommendations can be dawn.

The study was assessed surface water resources only, so groundwater availability of the catchment should be studied and supply enhancement and demand management options must be considered to balance future water resources and demands.

Future studies on Legedara river catchment modeling should address the issues related to water quality including sedimentation, nutrients, and evaluate best management practices to address different water quality issues in the catchments, land use change impacts on water recourses availability and climate changes using General Circulation Model. Similarly, future researches should be test other models such as soil moisture method usingWEAP model, WtBalM, RIBASIM and SWAM modelsin order to get more reliable water balances of the catchment. Moreover this, in this research, domestic, industrial and environmental flow requirements were only considered, therefore future research should be including all demand sites of the catchments.

In this study the final calibrated model parameters were transferred directly from gauged to ungauged catchment; however, future research should be test regression analysis.

In the study the uncertainty to relay on the outputs are likely to be, and a great deal of uncertainty surrounds such estimates. Analysts must always cope with a number of uncertainties in the valuation process. These gaps will cope by conducting sensitivity analysis and identifying the likely sources of uncertainty and also imagine the alternative futures.

The other thing which is highly recommended is that the weather stations should be improved both in quality and quantity in order to improve the model performance.

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7. APPENDICES

Appendix Table 7- 1: Corrected monthly Rainfall (mm) at Kebado station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1997	73.40	94.70	98.50	171.43	137.00	120.80	124.20	99.40	185.30	192.60	90.00	15.90	1403.23
1998	4.40	0.00	20.80	139.10	175.70	39.30	116.70	151.30	189.80	211.10	82.00	30.40	1160.60
1999	18.70	32.80	105.10	183.00	169.50	193.00	81.40	172.70	215.20	292.50	70.60	40.10	1574.60
2000	35.90	99.25	188.80	55.30	182.60	139.50	30.80	91.60	175.80	135.10	14.60	185.30	1334.55
2001	43.90	3.80	54.80	226.80	163.80	144.80	56.10	134.70	120.20	122.00	59.30	32.80	1163.00
2002	111.10	63.10	58.90	171.40	153.00	34.00	58.10	106.60	147.10	73.30	89.80	85.40	1151.80
2003	35.26	7.20	120.10	287.10	209.50	145.90	76.60	59.20	177.50	156.30	17.90	0.00	1292.56
2004	21.00	55.60	127.50	195.50	207.50	114.90	121.80	160.10	150.20	358.70	77.10	13.60	1603.50
2005	62.80	76.20	90.30	158.50	270.70	96.90	73.20	252.70	303.00	184.10	36.70	0.00	1605.10
2006	35.25	10.40	42.10	168.00	285.10	83.30	85.10	62.00	282.50	197.60	66.70	25.60	1343.65
2007	84.80	27.00	102.00	176.10	197.70	45.00	26.40	54.40	148.00	168.10	6.00	96.90	1132.40
2008	47.30	130.70	162.90	289.60	282.00	165.60	147.50	181.70	95.40	119.10	26.70	10.50	1659.00
2009	12.20	145.00	27.90	116.50	272.00	71.20	39.80	252.80	262.10	135.30	199.40	9.70	1543.90
2010	4.60	0.00	48.10	166.00	118.30	128.10	184.60	92.90	275.10	121.00	41.90	8.60	1189.20
2011	28.70	45.25	107.30	209.70	119.70	101.20	54.00	139.70	150.40	125.00	55.00	6.00	1141.95
2012	7.20	27.50	159.60	168.80	313.70	0.00	157.40	115.00	123.00	135.00	45.00	4.56	1256.76
2013	2.50	1.25	89.60	156.70	123.50	74.80	47.60	51.10	58.00	145.80	68.20	5.00	824.05
Mean	37.00	48.22	94.37	178.80	198.90	99.90	87.14	128.11	179.92	168.98	61.58	33.55	1316.46

Appendix Table 7- 2: Corrected monthly Rainfall (mm) at Dilla Mission station

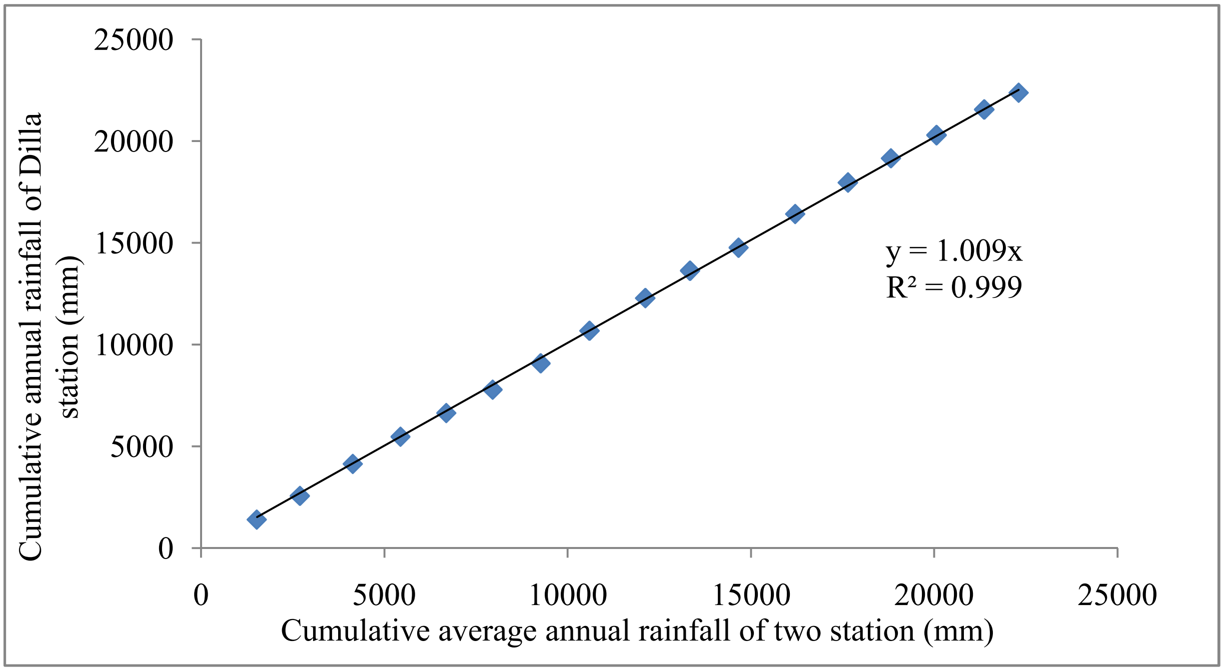
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1997	13.50	53.00	20.90	256.80	272.30	161.30	111.50	93.10	149.00	220.30	203.50	85.20	1640.40
1998	27.70	49.90	123.60	195.00	169.40	105.50	109.50	109.90	143.60	101.80	9.00	44.70	1189.60
1999	14.20	37.80	44.80	199.90	179.90	156.90	46.60	97.40	186.10	250.00	54.20	46.40	1314.20
2000	132.70	20.20	1.30	153.70	340.80	162.10	34.50	72.70	114.90	163.20	50.50	17.60	1264.20
2001	1.30	97.00	132.40	146.70	147.60	105.50	257.40	164.00	142.60	92.10	38.40	13.50	1338.50
2002	0.50	55.40	73.90	262.90	190.30	97.00	151.80	105.40	200.00	174.00	42.40	18.40	1372.00
2003	87.60	33.20	165.80	156.20	252.90	40.20	80.60	151.60	237.80	86.00	27.90	12.40	1332.20
2004	13.20	18.70	159.90	161.40	158.90	53.70	71.90	109.10	132.80	94.10	59.30	25.30	1058.30
2005	58.40	45.60	108.40	232.90	210.40	67.90	124.70	146.20	198.12	155.20	82.30	7.20	1437.32
2006	20.70	14.10	116.90	148.00	241.50	75.50	100.90	39.20	144.40	148.30	35.10	13.80	1098.40
2007	15.50	51.40	151.10	206.20	158.40	151.40	53.70	159.50	156.23	292.10	82.00	39.40	1516.93
2008	14.70	24.30	105.60	226.70	194.80	144.40	152.00	145.30	153.60	197.10	52.40	18.80	1429.70
2009	35.60	198.80	208.00	136.60	137.90	104.70	69.60	108.60	88.20	57.40	70.10	115.20	1330.70
2010	71.90	10.20	81.10	256.00	127.00	102.90	55.50	120.70	88.50	128.00	95.40	22.40	1159.60
2011	87.30	32.10	63.30	273.50	152.00	232.80	73.70	63.40	136.00	70.00	112.20	45.40	1341.70
2012	44.60	56.00	77.00	273.20	246.20	63.70	76.90	95.90	144.50	183.40	58.60	25.00	1345.00
2013	0.00	0.00	19.20	188.80	312.90	19.70	98.70	113.30	83.60	133.10	69.80	13.10	1052.20
Mean	37.61	46.92	97.25	204.38	205.48	108.54	98.21	111.49	147.06	149.77	67.24	33.16	1307.11

Appendix Table 7- 3: Monthly stream flow (m3/s) at Sala near Dilla University

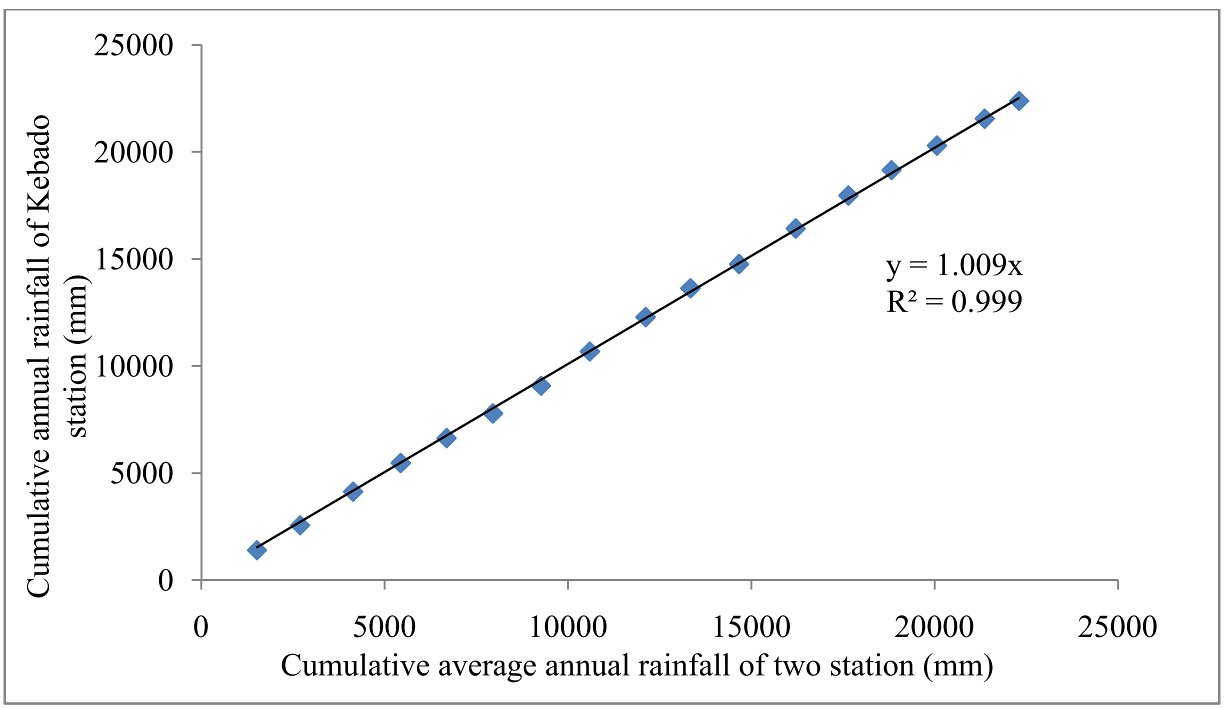
month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1997	0.45	0.53	1.25	2.15	1.72	0.98	1.32	1.35	3.92	2.60	2.12	0.85	19.24
1998	0.34	0.95	0.56	1.36	1.04	0.56	1.32	1.10	2.56	2.44	0.76	0.35	13.34
1999	1.05	0.45	1.53	2.36	4.70	3.44	3.94	3.49	3.71	7.25	2.53	0.56	35.02
2000	0.36	0.57	0.75	4.32	5.64	0.89	1.04	2.04	5.60	2.24	0.92	0.32	24.69
2001	0.31	0.40	4.10	4.56	0.64	1.25	1.88	1.34	3.04	2.35	0.56	0.36	20.79
2002	0.94	0.50	1.14	1.36	5.37	2.53	2.16	2.75	2.96	7.73	1.52	1.20	30.16
2003	0.65	0.50	1.67	1.52	3.98	3.21	2.93	6.23	2.56	3.25	2.51	0.65	29.66
2004	0.26	0.56	0.98	6.53	2.32	1.20	0.98	2.32	2.56	3.21	1.25	0.56	22.73
2005	0.71	0.36	1.23	2.52	8.17	1.23	2.12	4.49	3.50	5.68	3.21	1.04	34.25
2006	0.67	0.54	0.71	0.96	3.25	1.89	4.51	1.52	3.25	4.13	3.49	0.56	25.47
2007	1.08	0.87	0.72	0.88	3.26	0.97	2.05	1.89	0.97	1.56	0.78	0.93	15.95
2008	0.74	0.31	1.56	3.85	4.12	3.31	2.79	5.35	8.82	8.14	1.55	1.07	41.60
2009	0.38	0.34	2.10	5.95	2.80	3.91	0.60	0.62	4.63	4.46	3.21	0.76	29.75
2010	0.28	0.32	1.94	4.56	1.55	2.56	3.81	1.25	1.07	0.45	2.02	0.81	20.62
2011	0.71	0.62	1.98	2.11	4.50	0.65	2.10	5.12	3.12	3.12	0.95	0.39	25.36
2012	0.70	0.42	1.02	3.56	2.38	0.68	1.32	1.58	2.04	2.00	1.56	0.56	17.82
2013	0.51	0.39	0.87	3.25	1.12	1.26	0.95	1.56	2.05	5.25	1.23	0.97	19.41
Mean	0.60	0.51	1.42	3.05	3.33	1.80	2.11	2.59	3.32	3.87	1.77	0.70	25.05

Appendix Table 7- 4: Mean monthly weather data

Mean monthly weather parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax (oc)	29.70	30.40	30.50	28.30	27.20	26.60	25.70	26.00	26.50	26.90	28.00	28.80
Tmin (oc)	10.20	10.40	11.50	12.40	12.40	12.10	12.50	12.80	12.30	12.30	11.00	10.50
Sunshine (h)	7.70	7.10	6.60	5.90	6.20	4.90	3.30	4.60	4.70	5.50	7.50	7.90
Wind speed (m/s)	0.60	0.70	0.70	0.60	0.50	0.50	0.40	0.40	0.40	0.50	0.50	0.50
Wind speed (km/d)	51.84	60.48	60.48	51.84	43.20	43.20	34.56	34.56	34.56	43.20	43.20	43.20
RH-06 (%)	82.30	78.70	83.30	89.70	91.00	89.50	91.10	91.10	93.00	92.10	90.70	89.10
RH-12 (%)	46.60	43.60	49.20	59.70	65.50	66.00	68.60	66.20	66.20	62.00	59.10	52.30
RH-18 (%)	56.70	51.90	58.50	73.90	78.00	74.40	76.30	75.00	80.60	79.60	71.60	66.50
Average RH	61.90	58.00	63.70	74.40	78.20	76.60	78.70	77.40	80.00	77.90	73.80	69.30



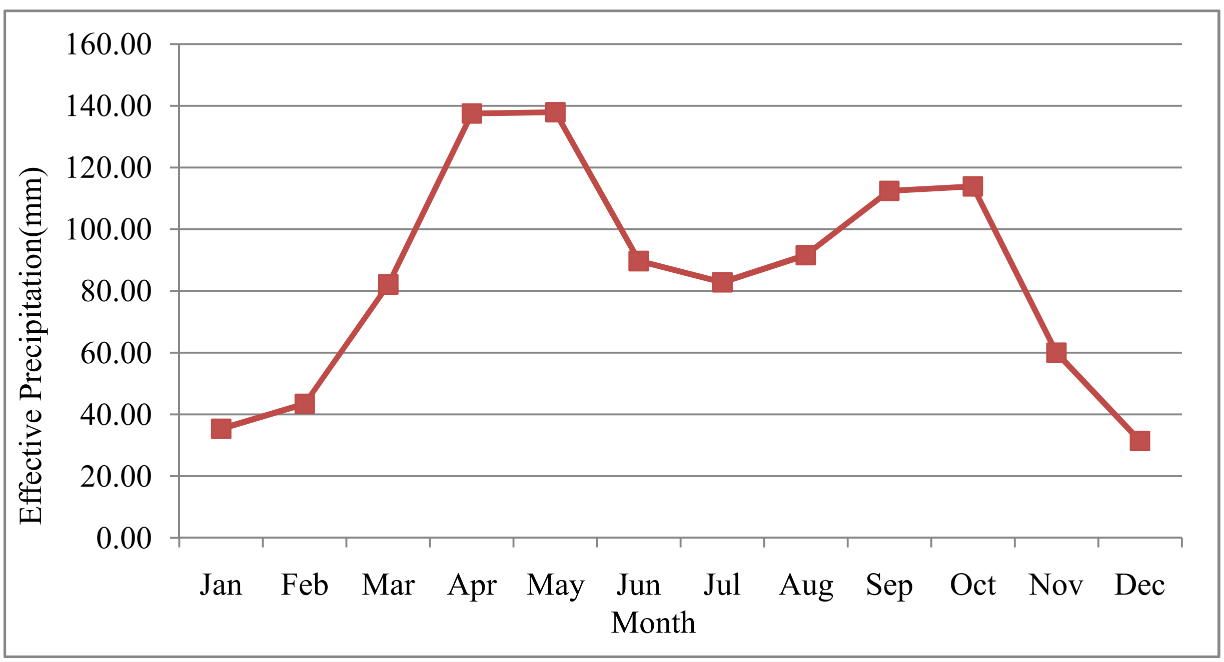
Appendix Figure 7- 1: Double mass curve analysis of Dilla Meteorological Station



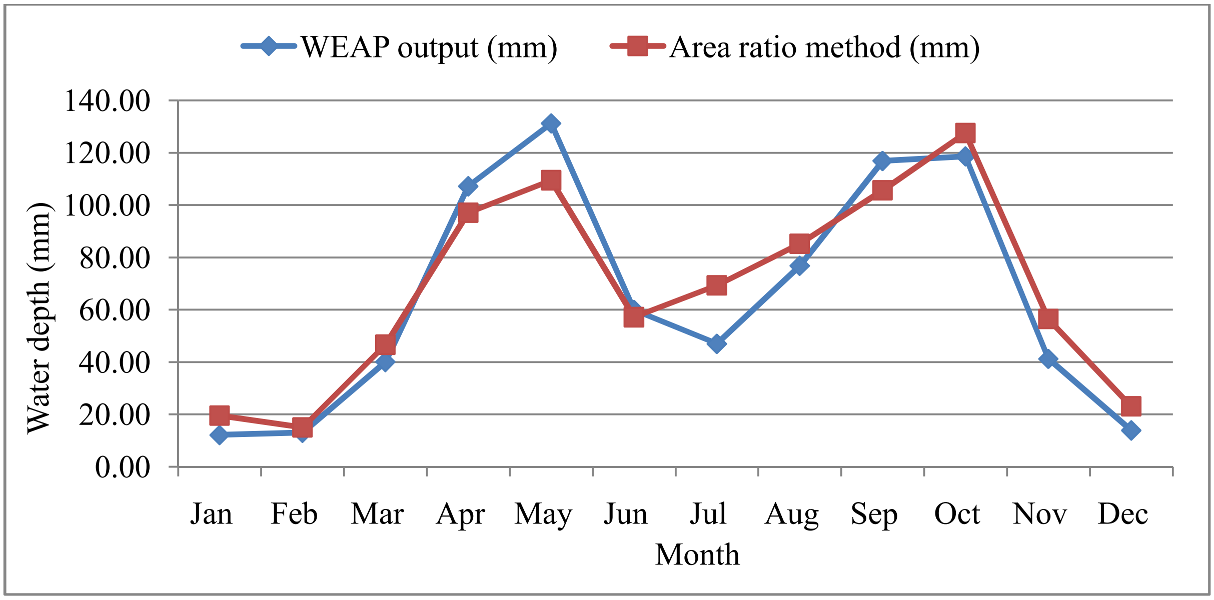
Appendix Figure 7- 2: Double mass curve analysis of Kebado Meteorological Station

Appendix Table 7- 5: Kc values for different land cover types

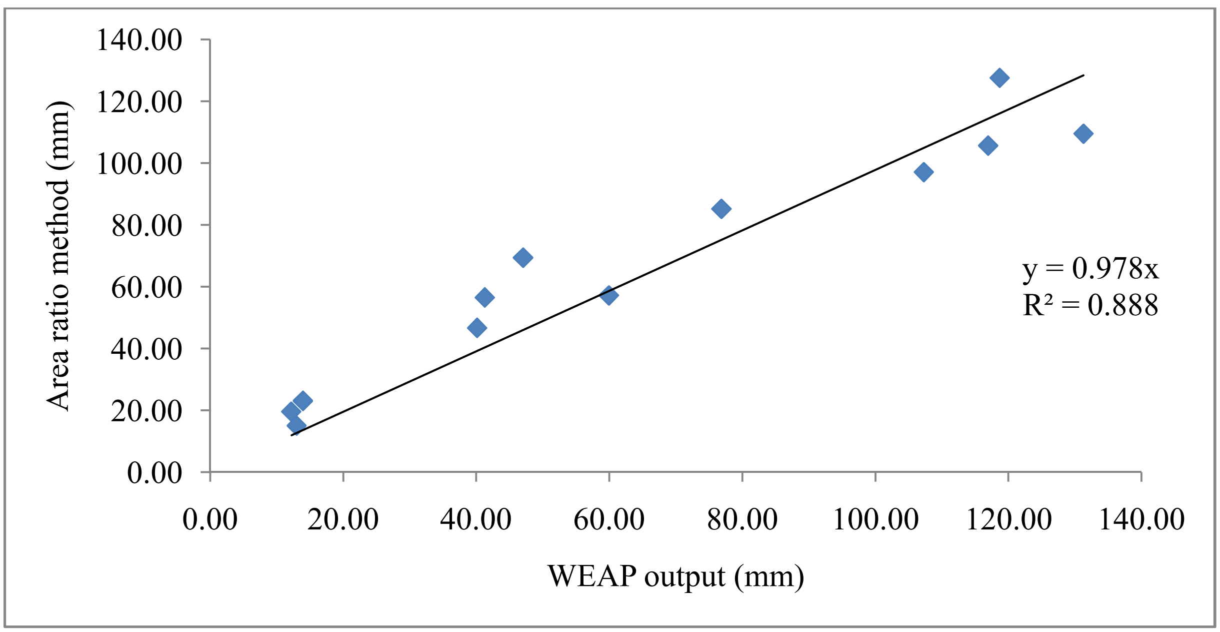
Land cover	Crop coefficient	Remarks
Cultivated land (all seasonal)	0.8	An average Kc for major crops on the area. Sources FAO I&D56.
Built up	0.2	Assume 20 % of the town is covered by with vegetation
Bare land	0 and 0.5	0 for dray season and 0.5 for wet season. Sources FAO I&D56.
Agro-forestry	1	For full ground cover and taller canopy height. Sources FAO I&D56.
Shrub land	0.8	An average Kc for shrub land. Sources FAO I&D56.



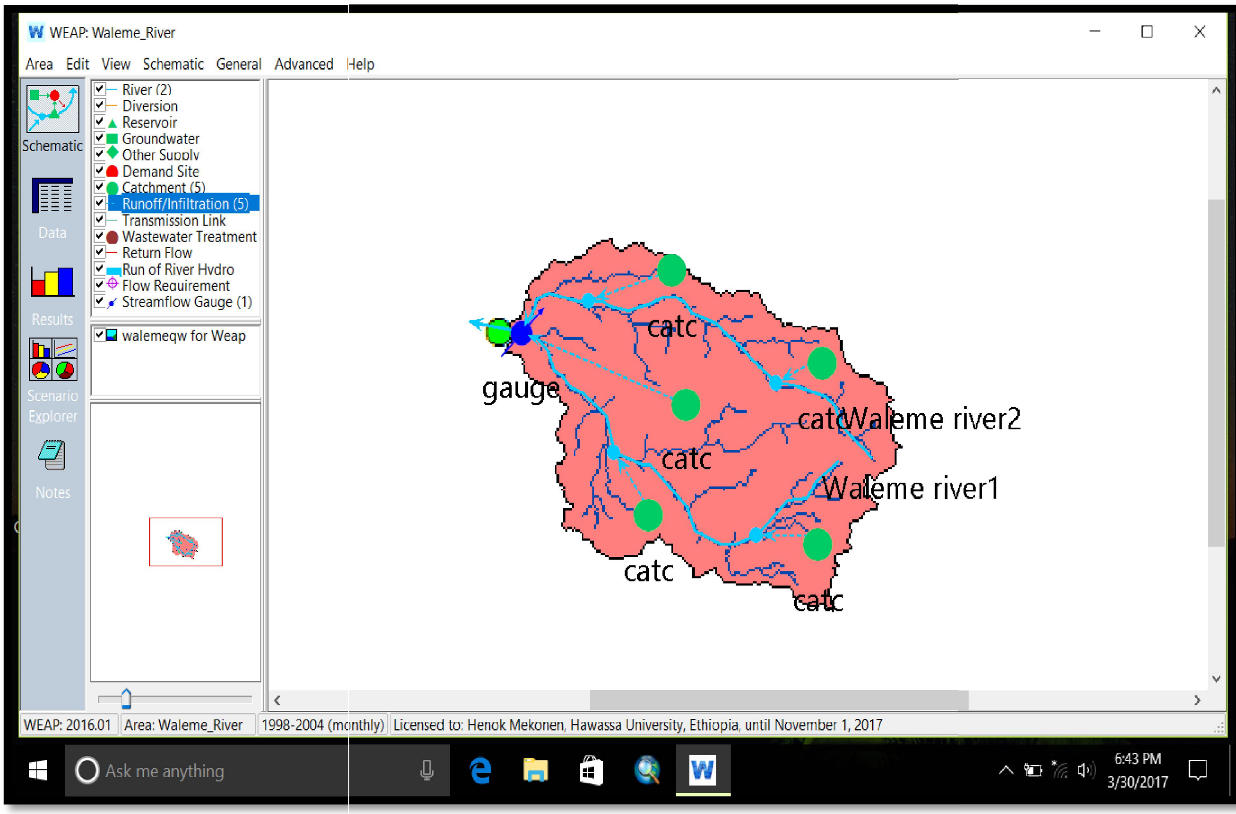
Appendix Figure 7- 3: Effective precipitation of Waleme catchment at Dilla Station (mm)



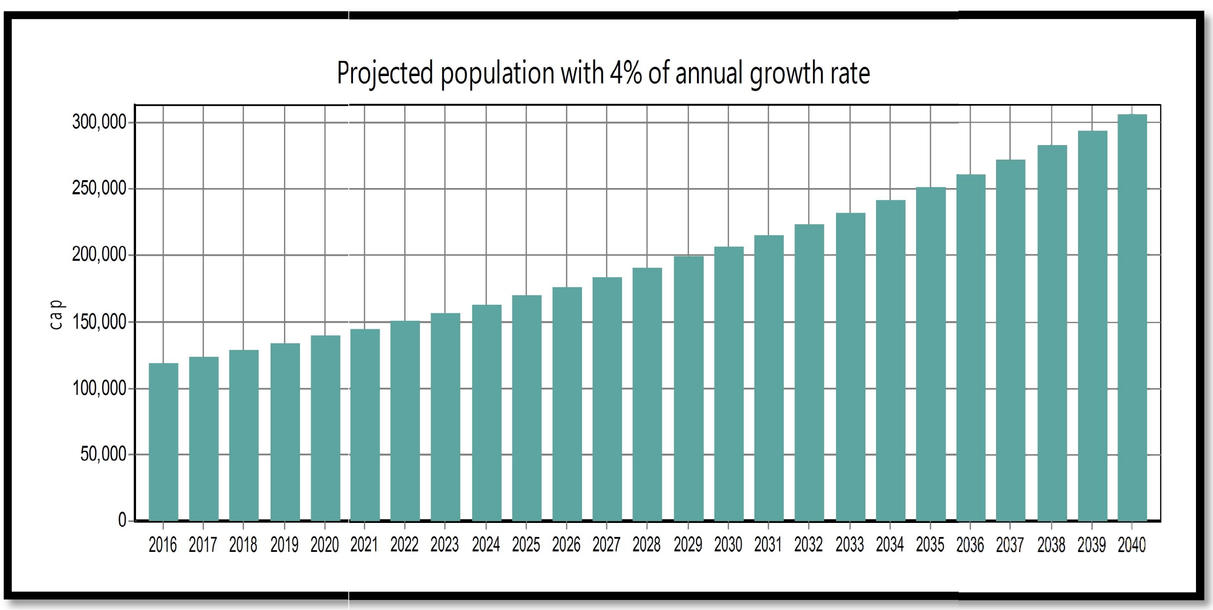
Appendix Figure 7- 4: Runoff of Legedara river catchment



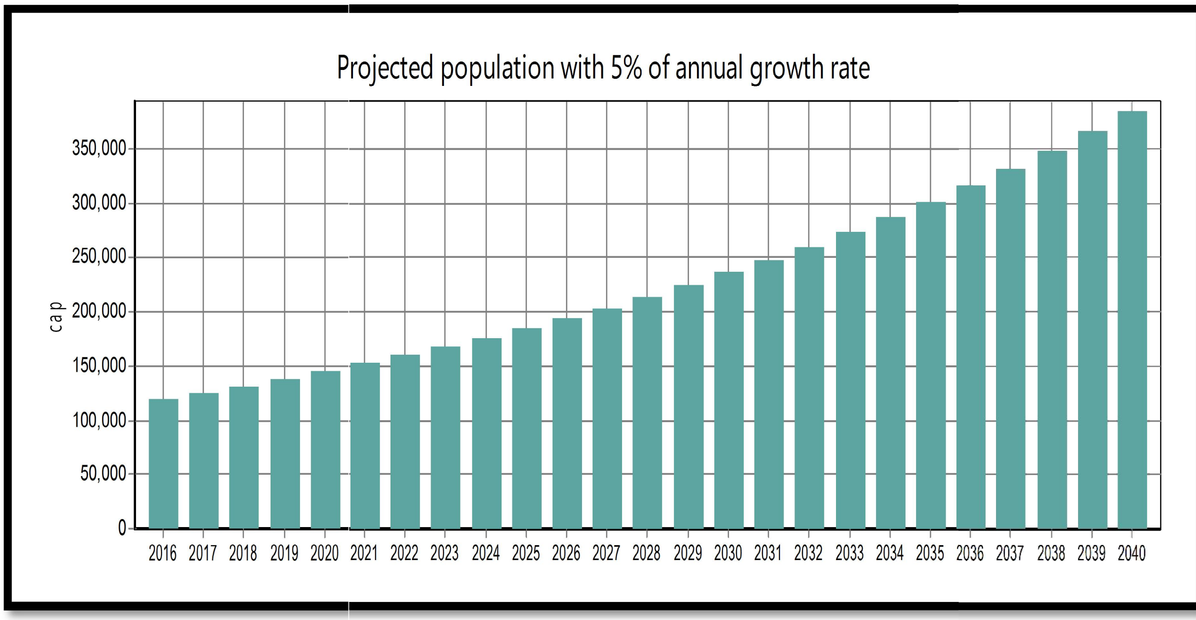
Appendix Figure 7- 5: Scatter plot of runoff of Area ratio Vs WEAP output



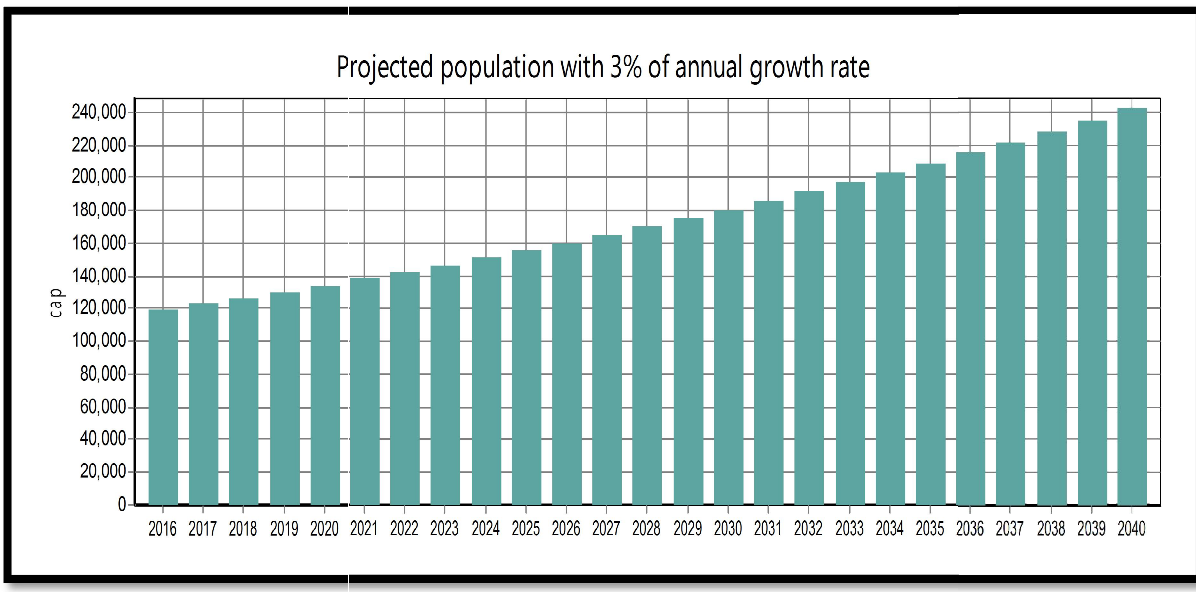
Appendix Figure 7- 6: Screenshot the schematic of Waleme river catchment of WEAP model



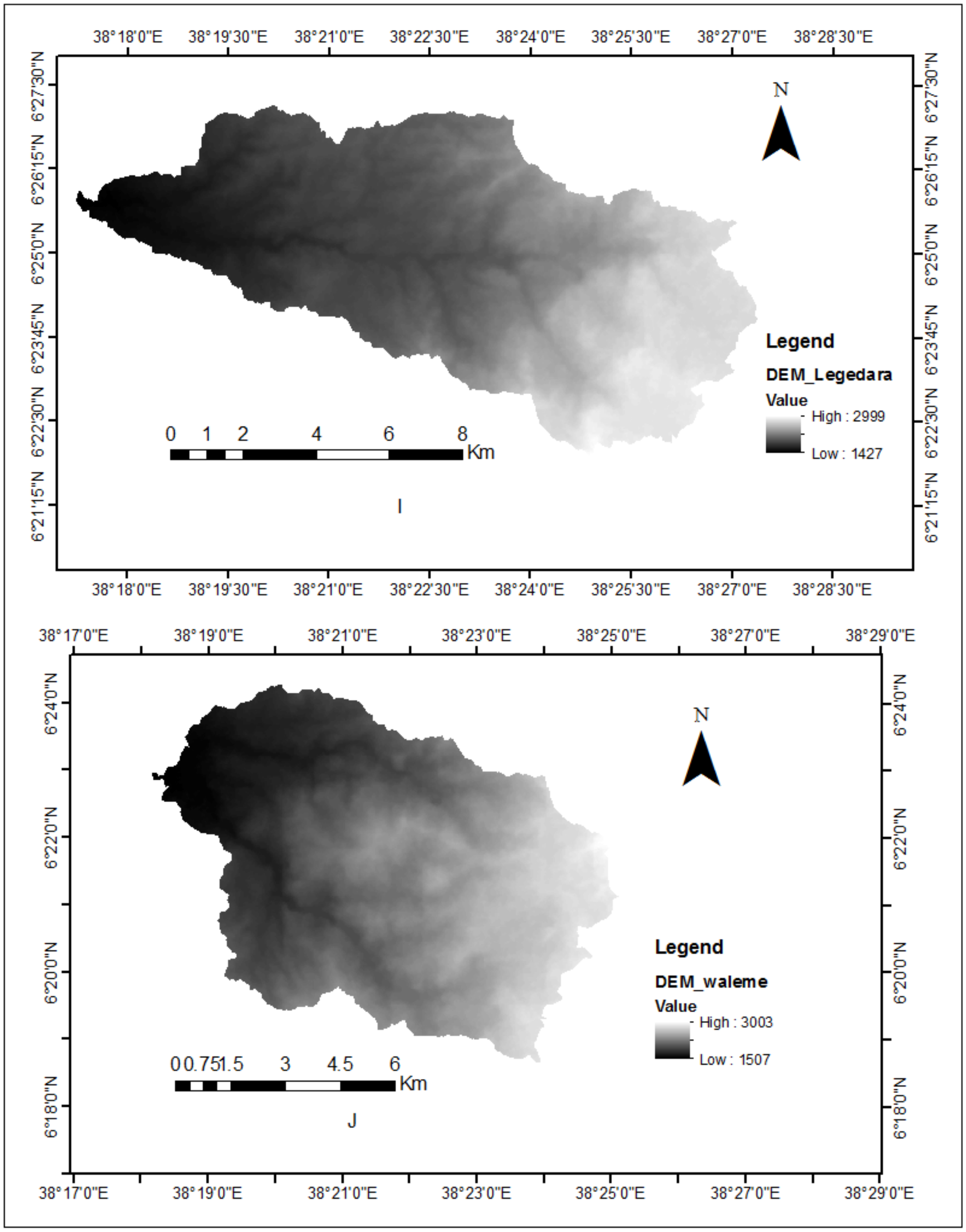
Appendix Figure 7- 7: Projected population of Dilla town with 4% of annual growth rate



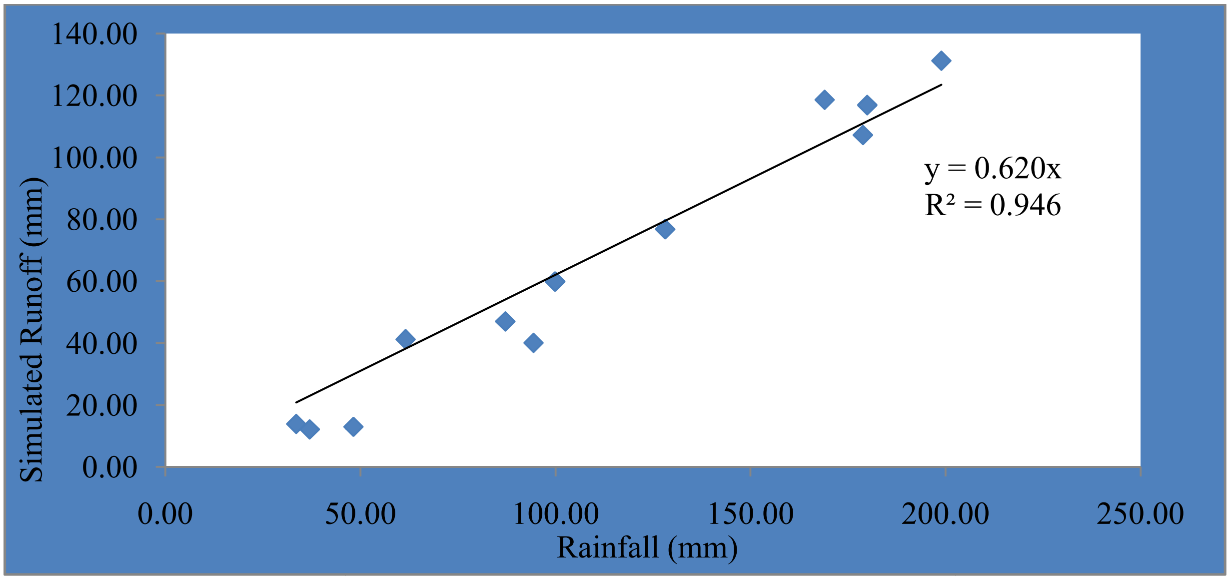
Appendix Figure 7- 8: Projected population of Dilla town with 5% of annual growth rate



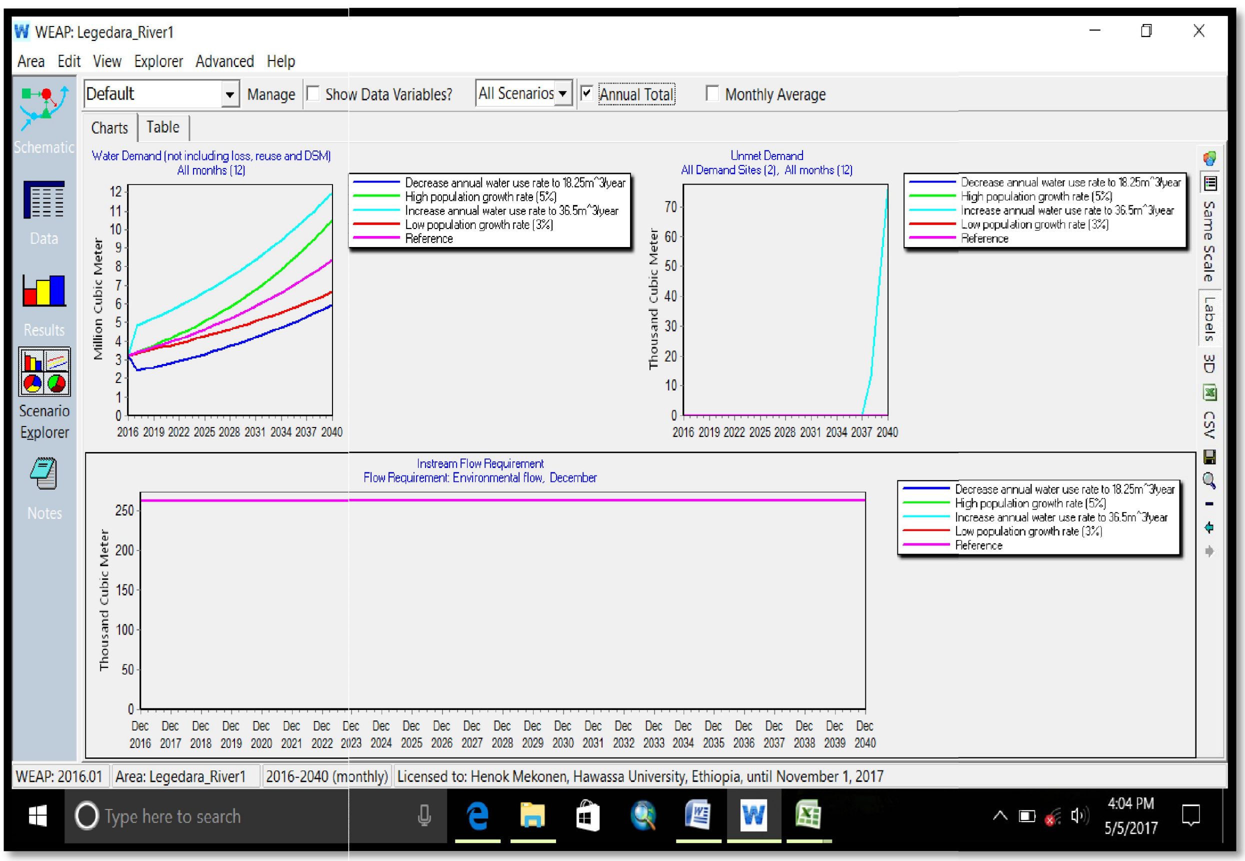
Appendix Figure 7- 9: Projected population of Dilla town with 3% of annual growth rate



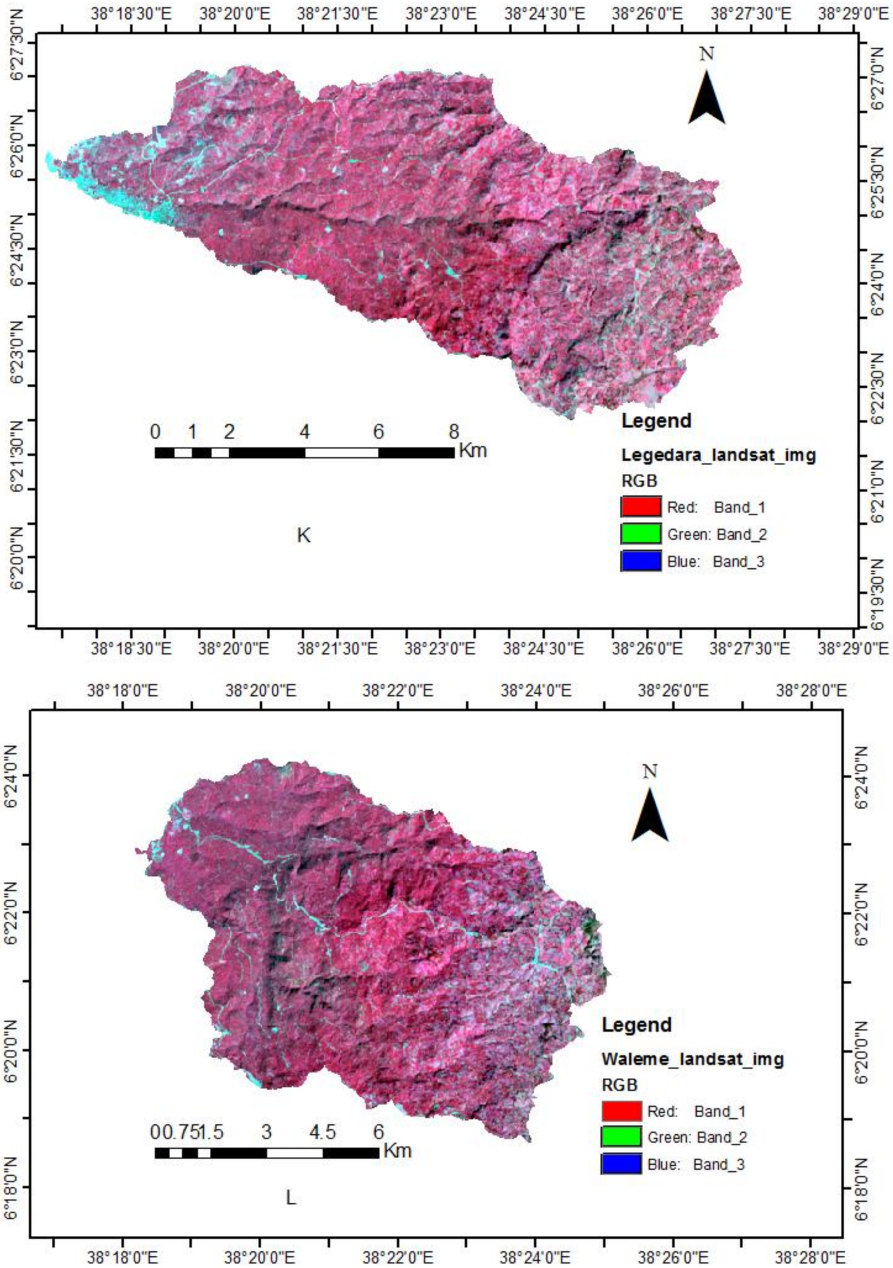
Appendix Figure 7- 10: DEM of Legedara (I) and Walemev (J) river catchment



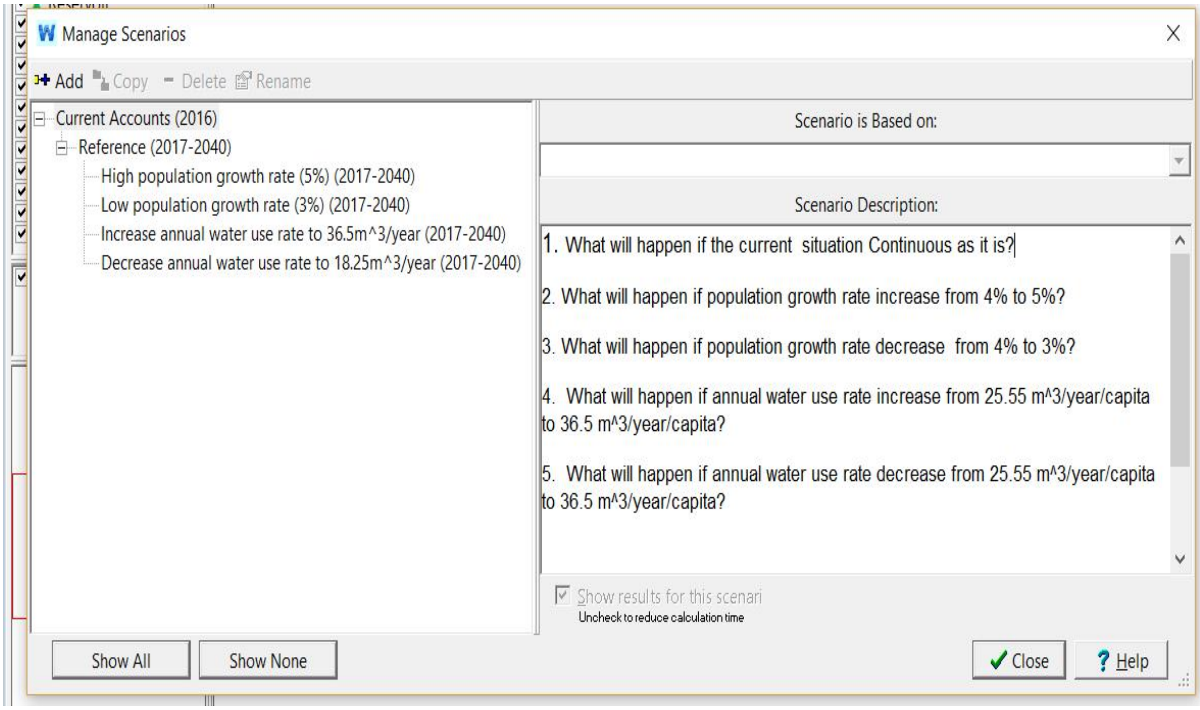
Appendix Figure 7- 11: Simulated Runoff Vs Rainfall of Legedara river catchment



Appendix Figure 7- 12: Scenario explorer of Legedara river catchment



Appendix Figure 7- 13: Landsat images of Legedara (K) and Waleme (L) river catchment



Appendix Figure 7- 14: Water demand scenario development in WEAP model

Procedures for the calculation of reference evapotranspiration:

Wind speed (U_2)

The wind speed measured at height other than 2 m can be adjusted according to the following equation:

$$U2 = Un \frac{4.87}{\ln(67.8h - 5.42)} \quad (7.1)$$

Where;

U_2 = wind speed at 2 m above ground surface, ms^{-1}

U_n = measured wind speed above the ground surface, ms^{-1}

h = height of the measurement above the ground surface, m

Slope saturation vapour pressure curve

For the calculation of evapotranspiration, the slope of the relationship between saturation vapour pressure and temperature is given as:

$$\Delta = 4098\left[\frac{0.6108 \exp\left(\frac{17.27 + Tmean}{T + 273.3}\right)}{(Tmean + 273.3)^2}\right] \quad (7.2)$$

Where,

Tmean = mean daily air temperature, ^{o}c.; exp = 2.7183 (base of natural logarithm)

Atmospheric pressure (P): A simplification of the ideal gas law, assume 20^{o}c for a standard atmosphere, can be employed to calculate in Kpa at a particular elevation.

$$p = 101.3\left[\frac{293 - 0.0065Z}{293}\right]^{5.26} \quad (7.3)$$

Where; Z= elevation above sea level, m; P = atmospheric pressure, Kpa

Psychrometric constant (γ)

Psychrometric constant is given as:

$$\gamma = \frac{CpP}{\varepsilon\lambda} = 0.000665P \quad (7.5)$$

Where,

γ = Psychrometric constant, Kpa^{o}c^{-1}; P = atmospheric pressure, Kpa; λ = Latent heat of vaporization, 2.45 MJKg^{-1}; Cp = specific heat of constant pressure, 1.013×10^{-3}MJKg^{o}c^{-1}

ε = ratio molecular weight of water vapour/ dry air = 0.622

Mean saturation vapor pressure (es).

The mean saturation vapour pressure for a day, week, decade or month should be computed as the mean between the saturation vapour pressure of the mean daily maximum and minimum air temperature for that period.

$$es = \frac{e(T\max) + e(T\min)}{2} \quad (7.6)$$

Where; es : mean saturation vapour pressure, e(Tmax): saturation vapour pressure of mean maximum air temperature, e(Tmin): saturation vapour pressure of mean minimum air temperature

Actual vapour pressure (ea)

The actual vapor pressure can also be calculated from the relative humidity.

$$ea = \frac{RHmean}{100}\left[\frac{e(T\min) + e(T\max)}{2}\right] \quad (7.7)$$

Where; ea : mean actual vapour pressure, e(Tmax): saturation vapour pressure of mean maximum air temperature, e(Tmin): saturation vapour pressure of mean minimum air temperature

Extraterrestrial radiation (Ra)

The extraterrestrial radiation Ra, for each day of the year and for different latitudes estimated from the solar constant, the solar declination and the time of year by:

$$Ra = \frac{240(60)}{\pi} Gscdr\left[(WsSin\varphi Sin\delta) + (Cos\varphi Cos\delta SinWs)\right] \quad (7.8)$$

Where;

Ra = extraterrestrial radiation, MJ m^{-2} day^{-1}; Gsc = solar constant, 0.0820 MJ m^{-2} min^{-1}; dr = inverse relative distance earth sun; Ws = sunset hour angle, rad; φ = latitude, rad; δ = solar declination

Mean daily solar radiation (Rs)

The average daily solar radiation expressed in MJ m^{-2} day^{-1} was required. A simple average of solar radiation values obtained from a weather station in period of 24-hour was required.

$$Rs = \left[as + bs\frac{n}{N}\right]Ra \quad (7.9)$$

Where,Rs = solar radiation (MJ m^{-2} day^{-1}); n = Actual duration of sunshine (hr); N = Maximum possible duration of sunshine (hr); $\frac{n}{N}$ = Relative sunshine duration (-); Ra =

extraterrestrial radiation (MJ m^{-2} day^{-1}); as and bs are regression constant, as =0.25 and bs = 0.5

Net shortwave radiation (Rns)

The net shortwave radiation resulting from the balance between incoming and reflecting solar radiation is given as:

$Rns = (1-\alpha)Rs$ (7.10)

Where;

Rns = net solar or shortwave radiation, MJ m^{-2} day^{-1}

α = albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop, dimensionless

Rs = the incoming solar radiation, MJ m^{-2} day^{-1}

Net outgoing long wave solar radiation (Rnl)

The net outgoing long wave radiation is given as:

$$Rnl = \sigma\left[\frac{(T\max + 273.16)^4 + (T\min + 273.16)^4}{2}\right]\left(0.34 - 0.14\sqrt{ea}\right)\left[1.35Rs - 0.35\right] (7.11)$$

Where;

Rnl = net outgoing long wave radiation, MJ m^{-2} day^{-1}

σ = Stefan-Boltzmann constant, 4.903 ×10-9 MJ K^4 m^{-2} day^{-1}

Tmax = maximum absolute temperature during 24-hour period (k = ^{o}c +273.16)

Tmin = minimum absolute temperature during 24-hour period (k = ^{o}c +273.16)

ea = actual vapor pressure, Kpa

Rs = the incoming solar radiation, MJ m^{-2} day^{-1}

Rso = clear sky-solar radiation, MJ m^{-2} day^{-1}

Net radiation (Rn) The net radiation is the difference between the incoming net shortwave radiation (Rns) and the outgoing net long wave solar radiation (Rnl).

$Rn = Rns - Rnl$ (7.12)