JIMMA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
JIMMA INSTITUTE OF TECHNOLOGY
FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING
DEPARTMENT OF HYDRAULIC AND WATER RESOURCES ENGINEERING
MASTERS OF SCIENCE IN HYDRAULIC ENGINEERING

Impact of Climate Change on Hawassa Lake Level Fluctuation

By: Amare Tura

A thesis submitted to the School of Graduate Studies of Jimma University in Partial fulfilment of the requirements for the Degree of Masters of Science in Hydraulic Engineering.

January, 2019

Jimma, Ethiopia

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Advisor: Dr. Fiseha Behulu

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CERTIFICATION

The undersigned certify that the Thesis entitled **Impact of Climate Change on Hawassa Lake Level Fluctuation** and hereby recommend for acceptance by the Jimma University in partial fulfilment of the requirements for the degree of Master of Science in hydraulic Engineering.

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ABSTRACT

One of the most important consequences of climate change is the changing nature of climate variables such as temperature and precipitation. This in turn leads to change in the hydrological cycle influencing the components of water balance of drainage basins by affecting the availability and distribution of water resources in space and time, stream flow, and Lake Level. In such circumstance, proper simulation of water resources and demands of the basin is needed to find effective solutions for saving the Lake. As a result, this study is intended to assess the impact of climate change on Hawassa Lake level fluctuation in the Central Rift Valley River Basin of Ethiopia. To achieve this objective, Water Evaluation and Planning (WEAP) Model were used to simulate water resource system of the Lake Hawassa catchment and to assess the impact of climate change on the Lake level. The performance of the model was assessed through calibration process of streamflow and lake level resulting NSE 0.93 and 0.9 respectively. Based on this, two Hypothetical scenarios were used to project future temperature and precipitation changes in the Lake catchment for the period of 2013 to 2035. Besides, the result from the two scenarios reveals that, a wetter and drier climate is anticipated for the lake catchment. In each scenario, the water resource implications were compared to the year of 2012 as a baseline for simulation. The results of projections indicates that, evaluation of the climate changes impact on Lake level fluctuations with Dry and Wet scenario the Lake level will reach 3.6m below and 3.72m higher than the observed level respectively by 2035. As a result, the simulation outcome reveals that both scenarios have a considerable impact on the Lake level fluctuation. Generally, the finding reveals that, global warming which is caused by climate change in the basin is a potential problem for effective water management in the Lake Hawassa catchment. Therefore, properly managing the consumption of the lake's water resource is desirable particularly and for other lakes in the basin generally.

Keywords: Climate Change, Lake Hawassa, Lake Level Fluctuation, and WEAP

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ACRONOMYS AND ABBREVATIONS

DEM	Digital Elevation Model
ENSO	El Niño-Southern Oscillation
ETo	Potential evapotranspiration
GCM	Global Circulation Model
GHG	Greenhouse Gas
GIS	Geographical Information System
HMS	Hydrological Modelling System
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-tropical Convergence Zone
IWRM	Integrated Water Resources Management
KW MODEL	kinematic wave model
M.A.S.L	Meters above Sea Level
MCM	Million Cubic Meter
MoWIE	Ministry of Water, Irrigation and Electricity
MoWR	Ministry of Water Resources
NMA	National Meteorological Service Agency
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe efficiency
PEST	Parameter Estimation Tool
RCM	Regional Climate Model
SNNP	South Nation Nationalities and People
WEAP	Water Evaluation and Planning
WWDSE	Water works design and supervision enterprise

CHAPTER ONE

INTRODUCTION

1.1 Background

Climate change refers to any significant change in the measures of climate variables lasting for an extended period of time. It includes major changes in temperature, precipitation, and wind patterns among other effects that occur over several decades or longer (USEPN, 2017). Nowadays, several research finding indicates that, climate change cannot be only explained by natural cause. Because, natural phenomenon do not fully explain the most observed warming problems especially since the mid-20th century as human activities have been the dominant cause of global warming today (USEPN, 2017).

Earth's average temperature has risen by 1.5^0C over the past century, and is projected to rise another 0.5 to 8.6^0C over the next hundred years. Small changes in the average temperature of the planet can translate to large and potentially dangerous shifts in climate and weather. Rising global temperatures have been accompanied by changes in climate especially several places have seen changes in rainfall, resulting in more floods, droughts, or intense rain, as well as more frequent and severe heat waves (NOAA, 2015).

The planet's oceans and glaciers have also experienced some big changes where oceans are warming and becoming more acidic, ice caps are melting, and sea leaves are rising. As these and other changes become more pronounced in the coming decades, they will likely present challenges to our society and our environment as water resources are important to both society and ecosystems. Human beings depend on reliable and clean supply of water for agricultural, energy production, navigation, recreation, and manufacturing. Many of these uses put pressure on water resources that is likely to be exacerbated by climate change (NOAA, 2015).

Across the world, climate change is likely increasing water demand while shrinking water demand and shrinking water supplies exists widely. This shifting balance would challenge water managers to simultaneously meet the need of growing communities, sensitive ecosystems, farmers' ranchers, energy producers and manufacturers (USAID, 2012).

However, in some areas including Africa, water shortage is fewer problems as compared to increases in runoff, flooding or sea level rise. These effects can reduce the quality of water and can damage the infrastructure that are used to transport and deliver water (NMA, 2007).

The IPCC, (2007) finding indicates that, developing countries such as Ethiopia are more vulnerable to climate change because of the less flexibility to adjust the economic structure and being largely reliant on agriculture.

Lakes are one of humanity's most important resources, especially in the tropics, where they are often viewed as highly productive biological systems. They provide water for consumption, fishing, irrigation, power generation, transportation, recreation, and a variety of other domestic, agricultural, and industrial purposes (Gebremichael, 2007).

In Ethiopia there are few studies conducted on the existing and future lake level connected to climate variability though there is huge doubt related to climate change in the country. Therefore, further understanding regarding the response of Lake Catchment using different hydrological model is more crucial for future water resource management strategies in the country. Among others, Lake Hawassa which is found in the South Nation Nationalities and People (SNNP) region is one of the terminal lakes of the rift valley basin in Ethiopia providing a major source of income through eco-tourism for the residents and input for the national economic development. Therefore, this study is primarily intended to deal about impact of climate change on Hawassa Lake level fluctuation using WEAP21 Model considering the possible outputs that the lake can provide for the development of the country if wisely and technically managed.

1.2 Statement of the Problem

Nowadays, the globe is facing a variety of climatic changes resulting alarming drought and flood perspectives interchangeably. Thus, the increasing concentration of greenhouse gases is expected to alter the radiative balance of atmosphere causing increases in temperature and changes in precipitation patterns and other climatic variables (IPCC, 2007). One of the most important impacts of climatic changes on the future society will be changes in water availability. Such hydrologic regime will affect nearly every aspect of human well-being, from agricultural productivity and energy use to flood control, municipal and industrial water use, and fish and wildlife management (NOAA, 2015 and IPCC, 2007).

The tremendous importance of water in both society and nature underscores the necessity of understanding how a change in hydrologic component within the change of climate variability could affect water bodies (NOAA, 2015). For instance, due to high temporal and spatial variability in rainfall, prolonged dry season, global environmental changes and population growth there is serious pressure on the water resources with consequences for the resident living at the foot of the lake.

Hawassa Lake which is prone to such spatial and temporal variation in climate emanating varies hydrologic responses. The level of the lake shows dramatic changes in the last few decades where it’s increasing in size and level for the last three decades is attributed to combined effect of land use and climatic changes (Gebreegziabher, 2006, Gebremichael, 2007, Dadi, 2013, and Dadi, 2015). Besides, a number of studies were conducted on the lake catchment though few of them investigated the impact of climate change on lake level fluctuation. This phenomenon demands a greater attention as the lake inundates the surroundings though highly overlooked by the necessary stakeholders. Therefore, assessing the lake’s level fluctuation in light of future climate change is very important for sustainable planning and management of the lake.

Generally, the purpose of this study was evaluating the possible impact of climate change on the lake’s catchment is essential to reduce the challenges of its future development as well as for managing the current water resources in study area.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of the study is to assess the impact of climate change on Hawassa Lake level fluctuation to provide possible remedial measures for sustainable use.

1.3.2 Specific Objectives

1. To identify the major water balance components of Lake Hawassa.
2. To evaluate the impact of climate change on Hawassa Lake level fluctuation.
3. To forward remedial actions for better management of the Lake.

1.4 Research Questions

This study poses and addresses the following basic questions.

1. What are the hydrologic components of the lake that controls the responses of the catchment?
2. What is/are the response of Lake Hawassa level fluctuation to the climatic changes?
3. What are the possible remedial actions to be provided for better management of the lake?

1.5 Scope of the Study

The scope of this study is delimited to assess the climate change impact on Lake Hawassa catchment using current observation meteorological data and future Hypothetical scenario to model rainfall-runoff and lake water balance by WEAP21 model. It is also confined to assess the lake’s future level of fluctuation as a result of climate change where comparison is made with respect to the base period observation. Thus, in this study the impact of climate change was assessed by using WEAP21 model assuming the land use/land cover will remain the same. However, the study also doesn’t consider the sediment inflow to the lake at current and future time horizons.

1.6 Significance of the Study

The study provides several importance’s to different actors. Frist, the finding of the study plays its own share to save the lake from the encountering problems regarding climate change. Second, it allow the planners, decision makers and any concerned bodies to understand the consequences of climate change on hydrological process and the impacts these on lake level fluctuation for water resource planning management and accordingly device decision and management support tools. Thirdly, it can serve as a possible reference for other researchers who are interested to this specific theme.

1.7 Limitation of the Study

This study has encountered several challenges. Among others, lack of sufficient and reliable data regarding the variability of the climate change on the fluctuation level of the lake is the main one. Besides, the model used for the purpose of this study is not easily accessible without license and it consumes time to be easily manageable to inter and analyze the data though it is technically handled.

1.8 Structure of the Study

This study is organized under five main chapters that are described as follows. Chapter one gives a general introduction to the study with its objective, significant of the study and research questions. Chapter two describes the reviewed literature related to the study. Chapter three deals with brief description of the study area, the material and methodology adopted for the study, data screening part and describe how the models are setup and data are analysed. Chapter four discuss the result of the study and lastly, chapter five provides the conclusions and recommendations.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

Climate change is a long-term shift in the statistics of the weather (including its averages). For example, it could show up as a change in climate normal (expected average values for temperature and precipitation) for a given place and time of year, from one decade to the next. It is know that the global climate is currently changing. The last decade of the 20th Century and the beginning of the 21st have been the warmest period in the entire global instrumental temperature record, starting in the mid-19th century (NOAA, 2015).

2.1.1. Overview of Climate Change

Climate change is the most serious problematic that the entire world is facing today. It is now widely accepted that climate change is already happening and further change is inevitable; Over the last century (between 1906 and 2005), the average global temperature rose by about 0.74^{o}C. This has occurred in two phases, from 1910s to 1940s and more strongly from the 1970s to 2006 (IPCC, 2007). Many studies into the detection and attribution of climate change have found that most of the increase in average global surface temperature over the last 50 years is attributable to human activities (IPCC, 2001). It is estimated that, for the 20th Century, the total global mean sea level has risen 12-22 cm, this rise has been caused by the melting of snow cover and mountain glaciers (both of which have declined in both hemispheres) (IPCC, 2007). The IPCC also notes that observations over the past century shows, changes are occurring in the amount, intensity, frequency and types of precipitation globally (IPCC, 2007). At this point it is worth mentioning the role and remit of the Intergovernmental Panel on Climate Change (IPCC).

The IPCC was established in 1998 by the World Meteorological Organization and the United Nations Environment Programme, and its role is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. Among the different assessment that are carried out by the IPCC, the most recent one that was published in 2007, states the projected global surface warming lies within the range 0.6 to 4.0^{o}C, whilst the projected see level rise lies within the range 0.18 to 0.59 m at the end of next century (IPCC, 2007).

2.2. Impacts of Climate Change on Water Resource and Reservoir

In order to originate adaptive policies for the reservoir as a multipurpose structure, all impacts of climate change on the operations of the reservoir need to be captured. An optimal adaptive policy then needs to be expressed which optimizes impacts on each of these multiple reservoir purposes.

Findings of the, IPCC (2007) strongly suggests that water resource respond to global warning in ways that will negatively impacted the water availability and water supplies. The climate change has also the potential to deteriorate the surface water quality due to increased evapotranspiration, lower flows and rivers becoming warmer, making the management of water treatment works and subsequent compliance with the drinking water quality regulations more challenging. The decrease in the runoff volume will lead to the decrease in the inflow to the reservoirs consequently; longer period might be required to fill the reservoir. As result of the increase in temperature the rate of evaporation from the reservoir open water surface may increase and this may create the reservoir to fail to supply at least the required amount of demand because of its depletion or decrease in the active storage volume and/or water level.

2.3. Climate Change in Ethiopia

Climate change is already taking place now, thus past and present changes help to indicate possible future changes. Over the last decades, the temperature in Ethiopia increased at about 0.2° C per decade. The increase in minimum temperatures is more pronounced with roughly 0.4° C per decade. Precipitation, on the other hand, remained fairly stable over the last 50 years when averaged over the country. However, the spatial and temporal variability of precipitation is high, thus large-scale trends do not necessarily reflect local conditions (Marius, 2012).

The future changes in precipitation and temperature as projected by various global climate models are summarized in Figure 2.1. Most of the global climate models project an increase in precipitation in both the dry and wet seasons. Studies with more detailed regional climate models, however, indicate that the sign of the expected precipitation change is uncertain. The temperature will very likely continue to increase for the next few decades with the rate of change as observed (Marius, 2012).

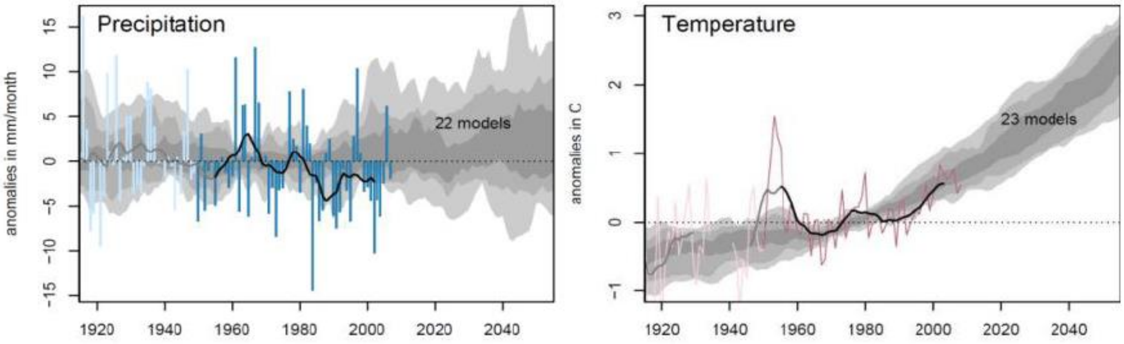


Figure 2.1 Observed precipitation changes in Ethiopia. Adopted from Marius (2012)

Annual average along with simulated changes by 22/23 global climate models (IPCC, 2007). The observed changes are likely flawed by network density changes and measurement errors in the first half of the 20th century (Marius, 2012).

2.4. Hydrologic Modelling

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Without going into too much detail, deterministic hydrologic models can be classified into three main categories (Cunderlik, 2003).

1. **Lumped Models:** Parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins. Parameters of lumped models often do not represent physical features of hydrologic processes and usually involve certain degree of empiricism. The impact of spatial variability of model parameters is evaluated by using certain procedures for calculating effective values for the entire basin. The most commonly employed procedure is an area-weighted average (Haan et al., 1982). Lumped models are not usually applicable to event-scale processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models (Beven, 2000).
2. **Semi-distributed Models:** Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin into a number of smaller sub basins. There are two main types of semi-distributed models: (1) kinematic wave theory models (KW models, such as WEAP), and (2) probability distributed models (PD models, such as TOPMODEL). The KW models are simplified versions of the surface and/or subsurface flow equations of physically based hydrologic models (Beven, 2000). In the PD models spatial resolution is accounted for by using probability distributions of input parameters across the basin.

3. **Distributed Models:** Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modelling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation-runoff behaviour. Distributed models generally require large amounts of (often unavailable) data for parameterization in each grid cell. However, the governing physical processes are modelled in detail, and if properly applied, they can provide the highest degree of accuracy.

2.5. Hydrologic Model Selection Criteria

There are numerous criteria which can be used for choosing the right hydrologic model. These criteria are always project dependent, since every project has its own specific requirements and needs. Further, some criteria are also user depended, such as personal preference for computer operation system, input/output management and structure, or users add on expansibility. Among the various project-depended selection criteria, there are four main common, fundamental ones that must always be considered (Cunderlik, 2003):

1. Required model outputs important for the needed purpose and therefore to be estimated by the model – does the model predict the variables required by the project such as peak flow, event volume and hydrograph, long term flows?
2. Hydrologic processes that need to be modelled to estimate the desired outputs adequately – is the model capable of simulating regulated reservoir operation, single event or continuous processes?
3. Availability of input data – can all the inputs required by the model be provided within the time and cost constraints of the project?
4. Price – does the investment appear to be worthwhile for the objectives of the project?

2.6. Water Evaluation and Planning (WEAP21) Model

2.6.1. Introduction to WEAP Model

The Water Evaluation and Planning System Version 21 (WEAP21) is an IWRM model that integrates water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements. WEAP21 was developed by the Stockholm Environment Institute's Boston Centre at the Tellus Institute. It considers demand priorities and supply preferences which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic approaches (Sieber and Purkey, 2015).

It introduces a transparent set of model objects and procedures that can be used to analyze a full range of issues faced by water planners through a scenario-based approach. These issues include climate variability and change, watershed condition, anticipated demands, ecosystem needs, the regulatory environment, operational objectives, and available infrastructure (Yates, 2005).

WEAP software has been supported to water planners from global organization and institutions. But, nowadays it is freely transferred to governmental and academic users from developing countries like Ethiopia. As a result, this study has applied WEAP21 in the Hawassa Lake catchment and the model is preferred to others because of: a) its robustness and ease of use depending on data availability; b) it can perform both lumped to distributed catchment hydrological simulation; c) it can handle aggregated to disaggregated water management demands of various sectors; d) it is appropriate for studying catchments with minimum to moderate data availability; and e) given the cost implication and data availability in the catchment.

2.6.2. Water Evaluation and Planning (WEAP) Applications Across the world.

As Holger et al (2011) applied WEAP to analyze the management of trans-boundary water resources in the Jordan River basin which is a very complex situation due to political conflicts in the region. Using WEAP and a dynamic consensus database, they tested various unilateral and multilateral adaptation options considering climate and socio-economic change.

Over exploitation of the large aquifer in Spain’s central arid region and the degradation of wetlands have been caused by exhaustive groundwater mining for irrigation which gave rise to notable social conflicts in recent years. WEAP was used to analyze water and agricultural policies to conserve groundwater resources and maintain rural livelihoods in the basin (Consuelo Varela-Ortega et al., 2011).

Besides, Ospina et al., (2011) used WEAP to make some baseline and adaptation strategy scenarios for water supply and demand in the Sinú-Caribe river basin in Colombia and project potential impacts of climate change in the basin.

The Niger River basin encompasses biosphere reserves, parks with a variety of wildlife, an important livestock activity, very fertile land for agriculture and a growing industrial sector. Management of water in the basin is very complicated due to socio-cultural, ecological and economic issues. In addition Mounir et al., (2011) used WEAP to optimize and allocate present and future Niger River resources between competing water demands.

Also Esqueda et al., (2011), assessed the impacts of climate change on the variation of water availability in the irrigation districts in the Guayalejo-Tamesí River Basin in Tamaulipas, México.

They used WEAP to define vulnerability of the water resources in the case study river basin, considering the effects of climate change on water availability in the municipal, industrial, and agricultural sectors.

Further Mugatsia, (2010) applied WEAP to assess the effect of proposed water infrastructure developments, policy and regulation under various scenarios in view of Water Act 2002 in Kenya. Using WEAP, the author divided the catchment into three sub-basins and developed two main scenarios that were compared to a reference scenario to assess the changes.

This study explored and evaluated the future scenarios concerning about high population growth, high technology, demand management, using the water year method, demand disaggregation, and supply preferences,(O'Connor et al., 2010) studied the total water management for urban water resources in the City of Los Angeles by using real data and WEAP model, to assist the planners and decision-makers in the development of management techniques to improve urban systems.

The study about water evaluation and the planning system in Kitui-Kenya clearly demonstrated that WEAP is a powerful framework in the evaluating of current and future options of water resources, and evaluation can be performed within a few minutes by adding more accurate data to increase the accuracy of the analysis and validation of results (Van Loon and Droogers, 2006).

WEAP was also applied as an urban water management tool in the study of water resources and city sustainable development of Heng Shui City in China (Ojekunle, 2006). This study pointed out that the availability and reliability of data are very important and must be analyzed carefully with good judgment, and the adoption of water demand management gives opportunities during normal hydrological years but not in dry years.

The application of WEAP models to major agricultural regions in Argentina, Brazil, China, Hungary, Romania, and the US, was analyzed by simulating future scenarios about climate change, agricultural yield, population, technology, and economic growth (Rosenzweig et al., 2004).

Climate change projection using global climate models (GCM) simulations indicates eventually larger changes in the 2050s and beyond, but the water for the agricultures is sufficient in most of the water rich areas (Rosenzweig et al., 2004). North eastern China shows the most stressed in water availability for agriculture and ecosystem services both in the current state and in the climate change projections (Rosenzweig et al., 2004).

2.6.3. Scenario Analysis with WEAP21 Model

WEAP model as described above allows for the analysis of various global change and water management scenarios. Scenarios are self-consistent story-lines of how a future system might evolve over time. These can address a broad range of "what if" questions like what if climate change alters hydrology? What if population increases?

This allows evaluating the implications of different internal and external drivers of change, and how the resulting changes may be mitigated by policy and/or technical interventions. For example, WEAP can be used to evaluate the water supply and demand impacts of a range of future changes in demography, land use, and climate. The result of these analyses can be used to guide the development of adaptation portfolios, which are combinations of management and/or infrastructural changes that enhance better water resources utilization in the future (Sieber and Purkey, 2015).

2.7. Related Studies on Hawassa Lake Catchments

A lot of researchers have discussed aspects of Lake Hawassa and the catchment at different times. Some of them with respect to the current study area are as follows.

The land use of Lake Hawassa catchment has been changed in the last few decades. The rise in the lake level has been explained in terms of increase in the runoff as a result of excessive deforestation (Dadi, 2013).

Besides Gebreegziabher, (2006) conduct on Assessment of the water balance of Lake Hawassa catchment using Thornthwait and Mather soil water balance procedure and spread sheet model. The result of the study revealed that the lake and the catchment water balance analysis indicating that the combined effect of climate and land use changes during the last 25 years most likely resulted in an increase of the catchment runoff and so the lake level.

The impact of Sedimentation and climate variability on the hydrological status of Lake Hawassa is conducted By Dadi in (2013). The main target of this study were to investigate causal variables for lake level variability in general and its resultant rise in particular applying diverse statistical techniques and forward the lake level tends to be high during El Niño and low during La Niña.

In addition, Dadi (2015) conducted on characterization of water level variability of Main Ethiopian rift valley lakes including Hawassa Lake by assessing their long-term water balance, their morphological characteristics and analysing their time series data of water level records. The study revealed that Lake Hawassa showed significant upward shift, which was likely caused by climate anomalies such as El Nine/southern oscillation (ENSO) phenomena.

CHAPTER THREE

METHODS AND MATERIALS

3.1. Description of the Study Area

3.1.1. Location

Lake Hawassa catchment is located in the central North-East of the Ethiopian Rift Valley Basin and the total area of the catchment is about 1300km^2, where 100km^2 is taken by the lake and 1200 km^2 of the catchment is occupied by surface land (figure 3.1). The geographical co-ordinates of the catchment are $6^0 45^1$ to $7^0 15^1$ North and $38^0 15^1$ to $38^0 45^1$ East latitude and longitude respectively. The Lake stretches 16km from the north east to south west direction and extends 8 km from north-west to south east direction having an approximate water volume 1.36 billion cubic meters. The maximum depth of the Lake is 21.6m with mean depth of 11m. The city of Hawassa, named after the lake, is located at 275 km south of the capital city-Addis Ababa and is established in the very eastern shore of the lake (MoWR, 2010).

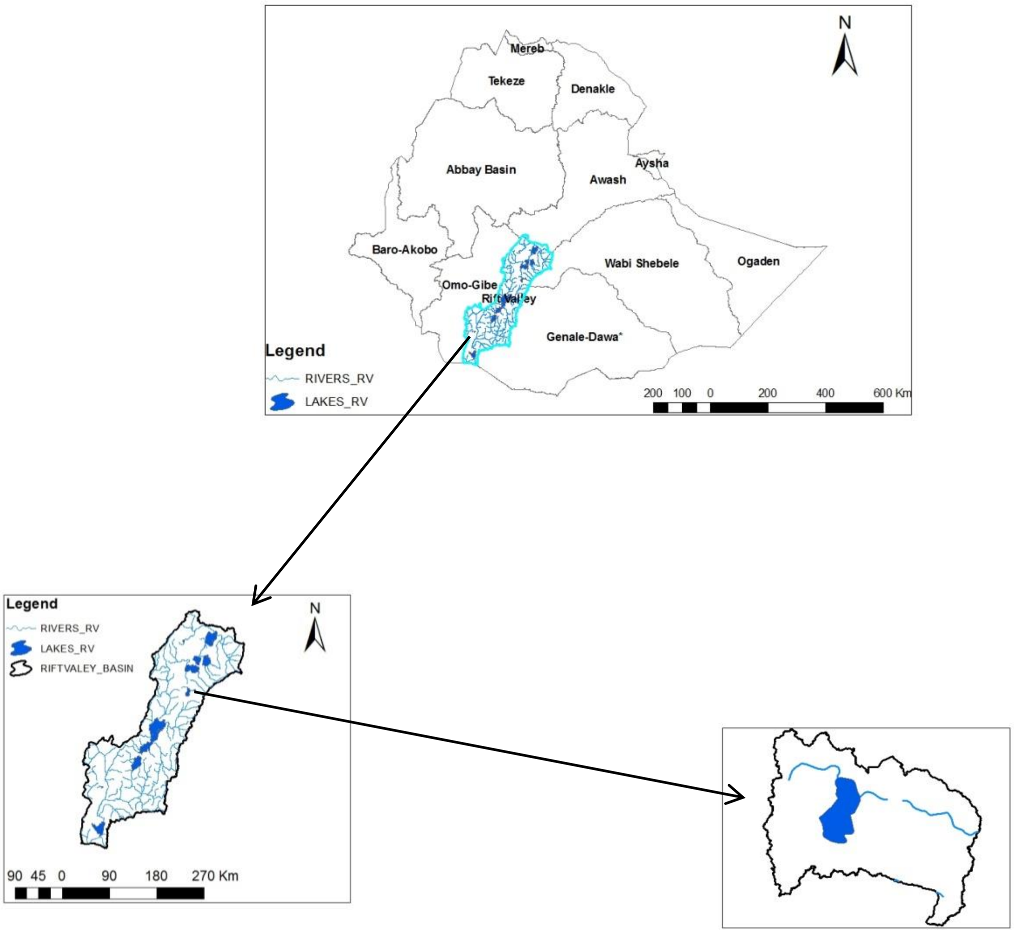


Figure 3.1 Location map of the study area

3.1.2. Topography

Majority of the Catchment is flat to gently undulating but bounded by steep escarpments. The altitude ranges from 1,680m at Lake Hawassa to 2,700m on the Eastern escarpment.

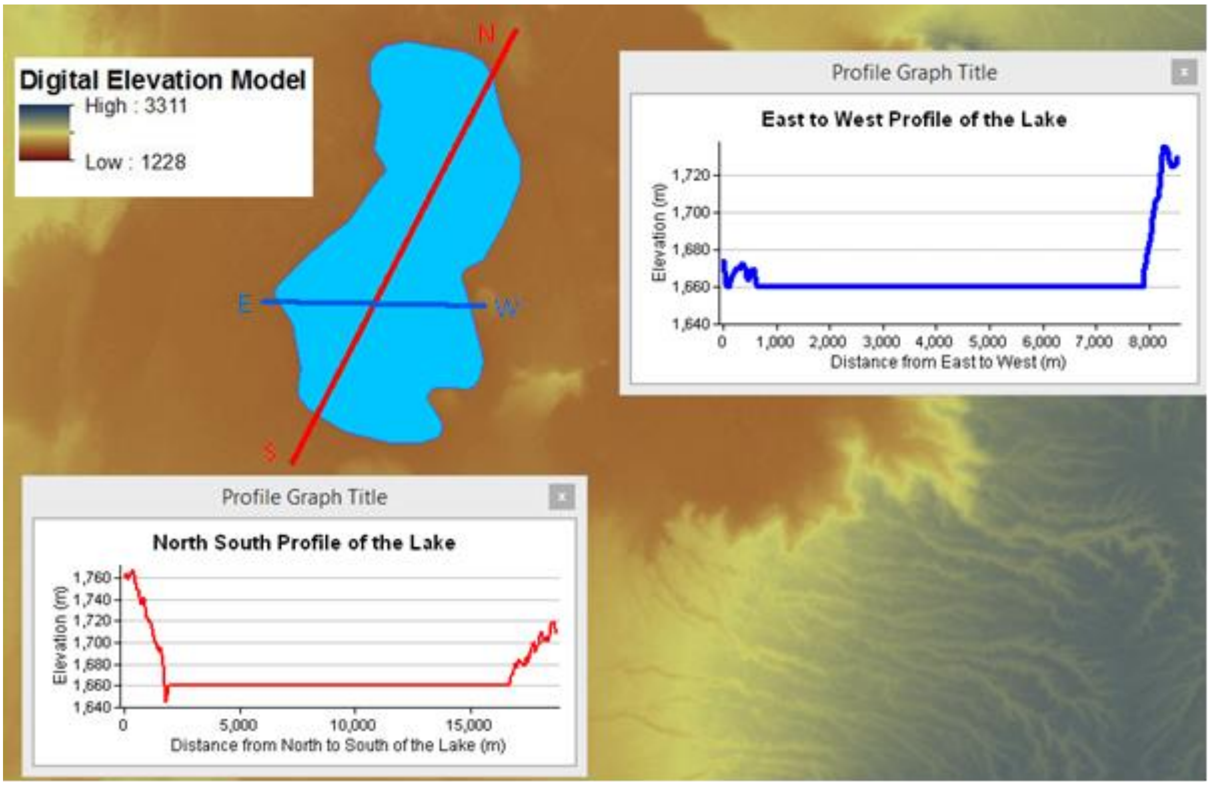


Figure 3.2 Profile graph of Lake Hawassa

3.1.3. Climate and Hydrology

The Lake Hawassa catchment is characterized by a sub-humid climate with annual precipitation variability. The moisture for precipitation in the area originates from south-west equatorial air stream, which moves northwards with inter-tropical convergence zone (ITCZ), (W.W.D.S.E, 2001). As computed from the long-term (1990-2012) rainfall occurs from March-October with mean monthly rain fall varying from 28mm in December to the maximum of 122mm in July. From the long-term temperature data, the mean annual temperature in the area is 20.2^{0}C. The hottest months are March and April whereas the coldest are November and December. Figure (3.3 and 3.4) shows the long-term average monthly distribution of rainfall and temperature at Hawassa meteorological station.

The Hawassa Lake catchment contains five sub-catchments: Dorebafena-Shamena, Wedesa-Kerama, Tikur Wuha, Lalima-Wendo Kosha and Shashemene- Toga. From these sub-catchments streams enter to Lake through a common Course. Flow-gauge station in the catchments, operated by the Ministry of Water, Irrigation and Electricity is located near to lake is named Dato village station that cover 625km^2 from the total catchment area and the rest was ungagged.

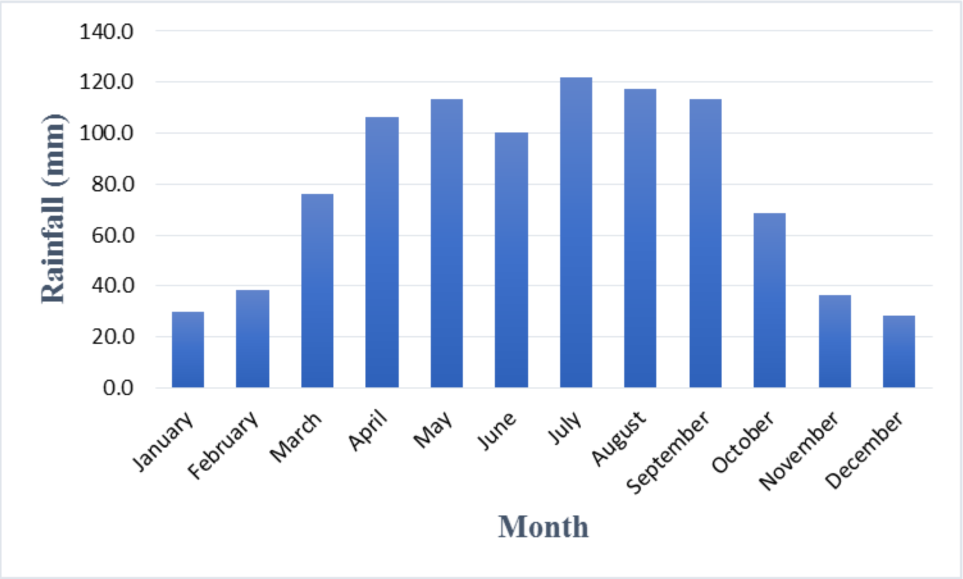


Figure 3.3 Mean Monthly Rain fall at Hawassa station

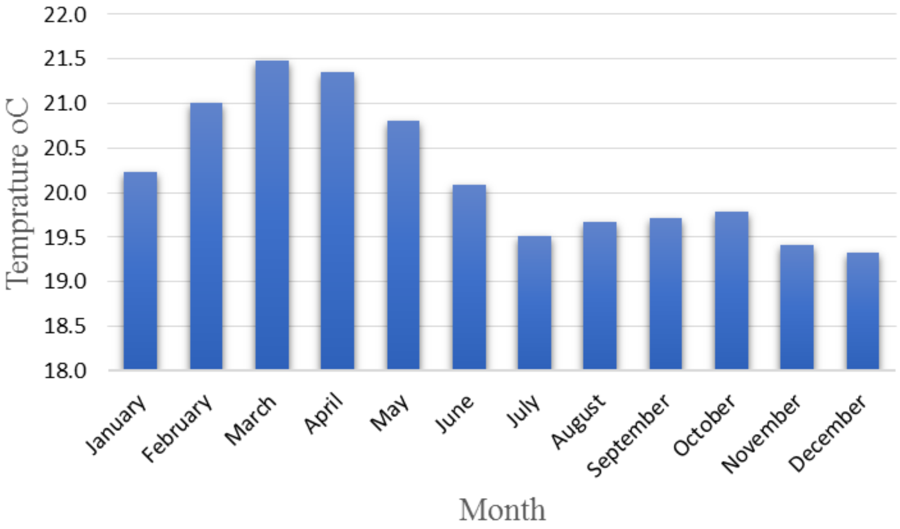


Figure 3.4 Mean Monthly air Temperature of Hawassa station

3.2. General Research Methodology

Basically, the general methodology for the study can be described by the following flow chart;

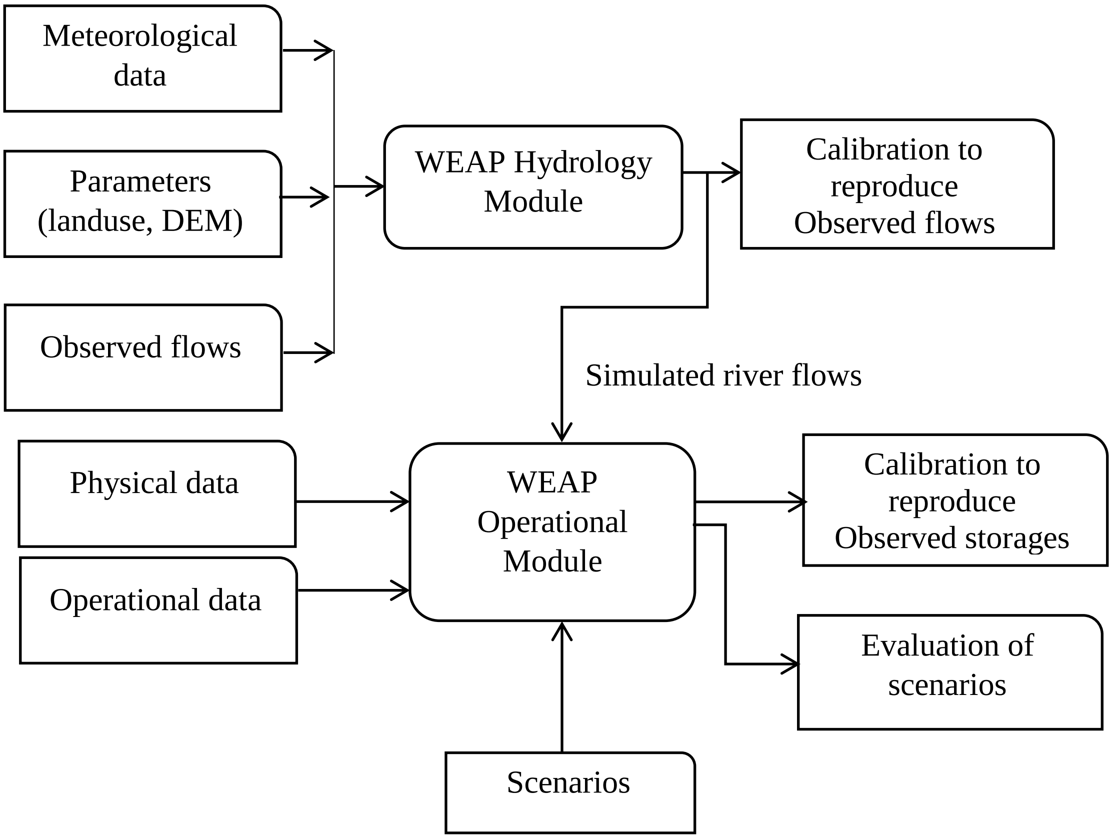


Figure 3.5 Conceptual Modelling Frameworks

3.3. Modelling process with WEAP

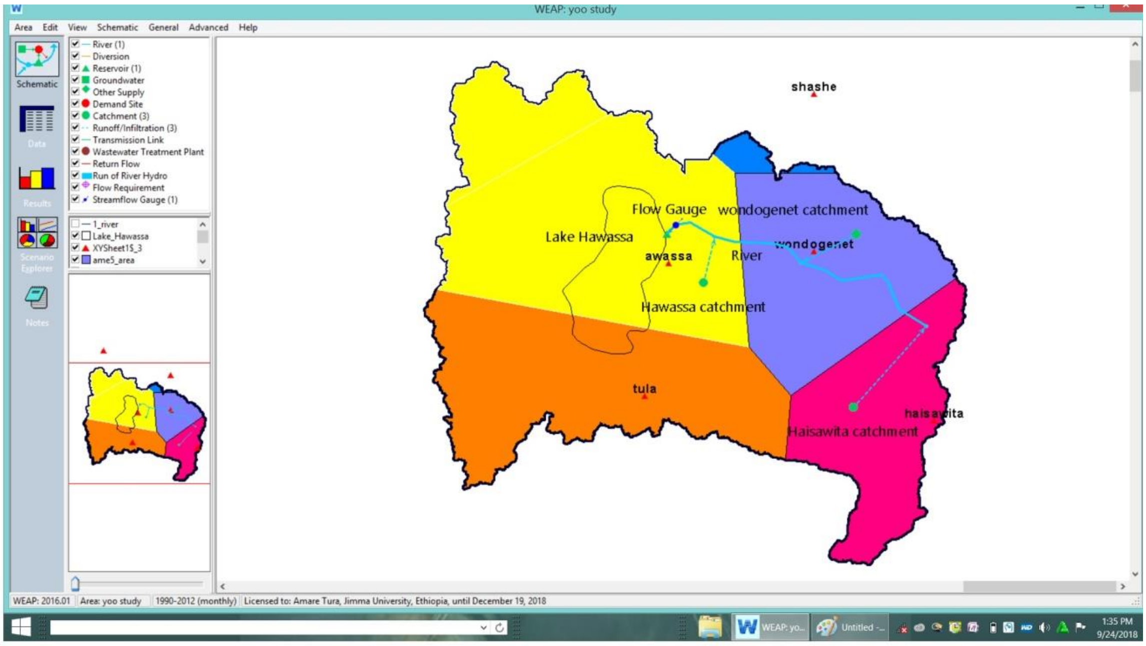
The WEAP21 software is a data-driven system that is customized to a specific river basin through a graphical user interface. A set of five different views are located on the left of the main screen along with 6 menus which compose the main user interface of WEAP (Sieber and Purkey, 2015). The five views are:

1- **Schematic View**: The spatial layout, which is called a schematic, is the starting point for modelling in WEAP. There are fourteen graphical options or interfaces including river, reservoir, and groundwater that one can visualize and simulate the physical features of water systems by dragging and dropping icons to create a node-link schematic diagram (Figure 3.6).

2- **Data View**: In the Data View, there is a hierarchical tree for entering, maintaining and managing data, and specifying assumptions for each scenario and for the current account (the existing condition). The hierarchical tree is composed of six major categories:

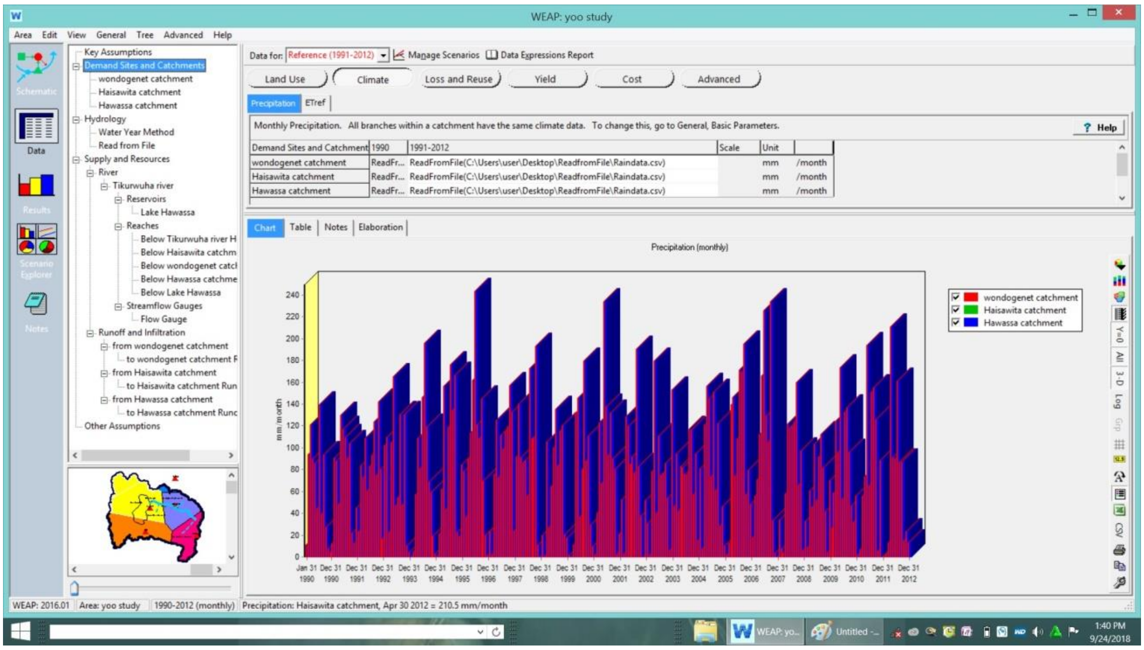
Key Assumptions, Demand Sites, Hydrology, Supply and Resources, Water Quality, and Other Assumptions (Figure 3.7).

3- **Results View**: The purpose of this view is to report the results of scenario calculations in the form of a graph, table or map.



WEAP: 2016.01 | Area: yoo study | 1990-2012 (monthly) | Licensed to: Amare Tura, Jimma University, Ethiopia, until December 19, 2018

Figure 3.6: Schematic view of WEAP



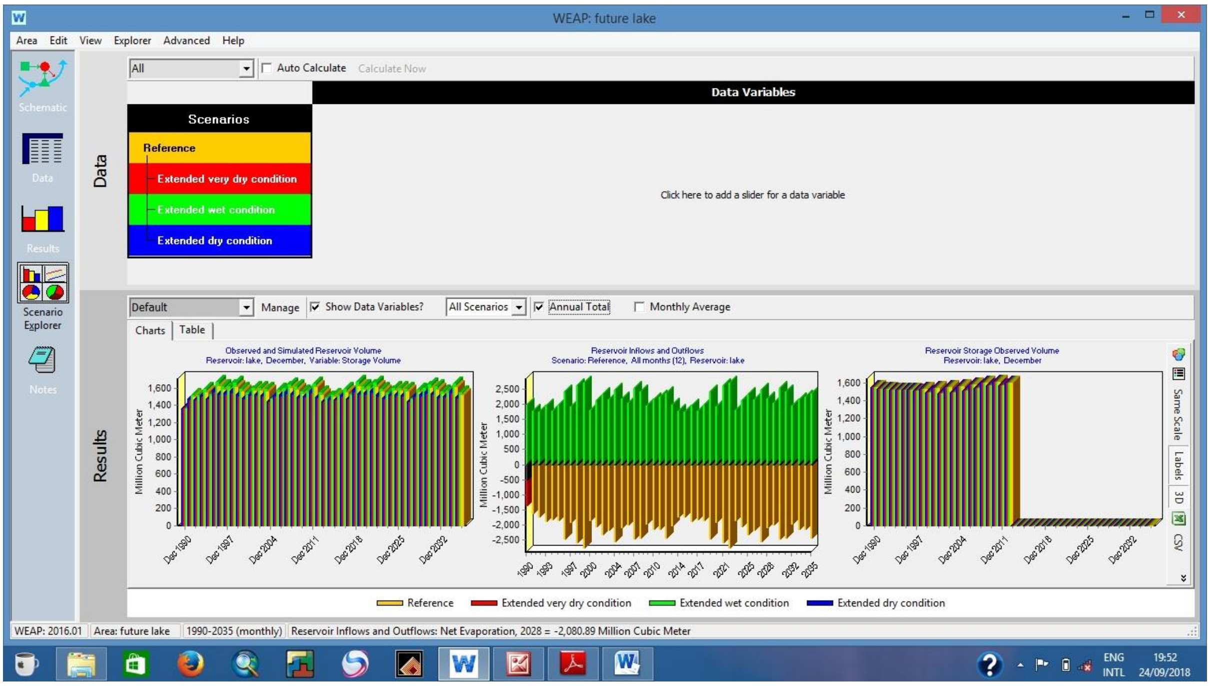
Monthly Precipitation. All branches within a catchment have the same climate data. To change this, go to General, Basic Parameters.

Demand Sites and Catchment	1990	1991-2012	Scale	Unit	
wondogenet catchment	ReadFr...	ReadFromFile(C:\Users\user\Desktop\ReadfromFile\Raindata.csv)		mm	/month
Haisawita catchment	ReadFr...	ReadFromFile(C:\Users\user\Desktop\ReadfromFile\Raindata.csv)		mm	/month
Hawassa catchment	ReadFr...	ReadFromFile(C:\Users\user\Desktop\ReadfromFile\Raindata.csv)		mm	/month

WEAP: 2016.01 | Area: yoo study | 1990-2012 (monthly) | Precipitation: Haisawita catchment, Apr 30 2012 = 210.5 mm/month

Figure 3.7: Data view

4- **Scenario Explore View**: This view is for displaying multiple required charts, or/and tables to explore effects of scenarios on the different parts of the water system (Figure 3.8).



Reservoir Inflows and Outflows: Net Evaporation, 2028 = -2,080.89 Million Cubic Meter

Figure 3.8: Scenario explore view

5- **Notes View**: This is the place for entering and writing documents for the current account, references, and scenarios.

The modelling of a watershed using the WEAP21, (Sieber and Purkey, 2015) consists of the following steps:

i. Definition of the Study area and time frame. Setting up the spatial boundary of the study area, system components, and the time frame that includes the last year of scenario creation (last year of analysis) and the initial year of application.

ii. Current account creation by specifying demands and supplies nodes of the study area. This is very important since it forms the basis of the whole modelling process. The current account is also used for calibration of the existing situation in the water systems being modelled.

iii. Creation of scenarios based on future assumptions and expected increases in the various indicators. This forms the core or the heart of the WEAP model since this allows for possible water resources management processes to be adopted from the results generated from running the model. The scenarios are used to address a wide ranges of “what if” questions such as:

   - What if climate change alters the hydrology?
   - What if reservoirs operating rules are altered?
   - What if groundwater supplies are fully exploited?

   Scenarios creation can take into consideration factors that change with time.

iv. Evaluation of the scenarios with regards to the availability of the water resources for the study area. Results generated from the creation of scenarios can help the water resources planner in decision making, which is the core of this study.

3.4. Supply and Resources

The Supply and Resources section is used to calculate water inflows to and outflows from every node and link (such as rivers, reservoirs, and groundwater) in the system in monthly time steps (Sieber and Purkey, 2015). This section of the model simulates monthly river flows and tracks interaction of water surface, groundwater and reservoir storage. Subsections of Supply and Resources are:

I. **Transmission Links:** Transmission links, which convey water from supplies (like rivers) to reservoirs, to demand sites are subjected to evapotranspiration, infiltration, capacity of supplies, and other constraints.

II. **Rivers and Diversions:** This subsection simulates in-stream flows, reservoir operation, interaction of surface water-groundwater, and stream-flow gages.

III. **Groundwater:** This subsection simulates groundwater along with storage, natural recharge, and aquifer properties.

IV. **Local Reservoirs:** This subsection simulates reservoirs which are not located on the main stream of the river.

V. **Other Supplies:** This is used to model other sources of water, like inter-basin transfers, that are not directly modelled in WEAP.

VI. **Return Flows:** This subsection can simulate routing of wastewater or return flows from demand sites to wastewater treatment plants, groundwater, and/or rivers.

3.5. Hydrologic Inflow Simulation

One of the reasons for modelling water systems is to understand how a catchment responds to a variety of hydrologic conditions (e.g., month to month and year to year). The Software WEAP can simulate and project surface water hydrology over the study period using four methods, which includes: The Water Year Method, Expressions, Catchments Runoff and Infiltration, and the ReadFromFile Method (Sieber and Purkey, 2015, Yates, 2005). Using these methods, one can model monthly inflows to appropriate surface and ground water locations (or nodes).

3.5.1 Catchments Runoff and Infiltration

The WEAP software allows one to simulate catchment runoff using the Soil Moisture Method or using the Rainfall Runoff Method. The simulated runoff is then directed to rivers and groundwater nodes using a Runoff/Infiltration link. This was the method used in this study.

3.6. Catchment Hydrology

There are four methods presented in WEAP21 for simulating catchment processes. These are Irrigation Demands Only versions of the FAO Crop Requirements Approach, the Rainfall Runoff Method, the Soil Moisture Method, and the MABIA Method. These methods range from simple to complex and the choice of method depends upon the purpose of the analysis and the availability of required data (Wigley, 2007).

3.6.1 Rainfall Runoff Method (based on the FAO Crop Requirement)

This is similar to the Irrigation Demands Only method to calculate evapotranspiration using crop coefficients. The remainder of precipitation that 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. This was the method used to simulate river flows in this study.

3.7 Calculation Algorithms

The calculation process, as comprehensively described in the WEAP User Guide, is based on mass balance of water for every node and link and is subject to demand priorities, supply preferences, and water requirements. Calculation starts from the first month of the Current Account year to the last month of the last scenario. For non-storage nodes, such as points on a river, the currently month’s calculation is independent from the previous month’s calculation. For storage nodes, such as reservoirs, soil moisture, or aquifer storage, the storage for the current month depends upon the previous month’s value. Whatever water enters the system during a month, it will either be stored in a reservoir, aquifer, or catchment soils, or leave the system by demand site consumption or evapotranspiration.

3.7.1 Catchment Calculation

3.7.1.1 Rainfall-Runoff method Calculation

The rainfall runoff method was used to simulate river flows in this study; this was constrained by the type of data available (Rainfall, Evaporation and crop data). The following type of data is required to perform rainfall-runoff simulation using this method;

- Land use (Area, Kc, Effective precipitation)
- Climate (precipitation and ETo)

Where Kc- crop coefficients and ETo is the reference crop evapotranspiration.

3.7.2 Reservoir Calculation

In general, the main purpose of the reservoir is to provide a source of water for demand sites during dry periods. WEAP can simulate a reservoir taking account the reservoir’s operating rules, downstream requirement priorities, net evaporation on the reservoir, and hydropower generation. There is a terminal lake in the catchment; these were simulated as reservoir within the Tikurwuha River that flows into the lake. The interactions of surface water and ground water were not simulated in this study. Seepage losses from reservoirs can be significant, particularly in lakes and unlined reservoirs. But for this study, a constant reservoir loss to ground water 58Mm^3/year was used (Gebreegziabher, 2006, Dadi, 2013). Reservoirs can use a zone-based operation and reservoir storage is separated into four zones (Figure 3.9):

1. The Flood- control zone (Sf): defines the storage that can temporarily hold water therefore release can be controlled. Thus storages above the flood control storage are spilled before the end of the time step.
2. The Conservation zone (Sc): is the storage available for downstream demands at full capacity.
3. The Buffer zone (Sb): is a storage that can be used to control and regulate water demands during shortages. When reservoir storage falls within the buffer storage, water withdrawals are effectively conserved via the buffer coefficient, bc, which determines the fraction of storage available for release.
4. The Inactive zone (Si): is the dead storage that cannot be utilized.

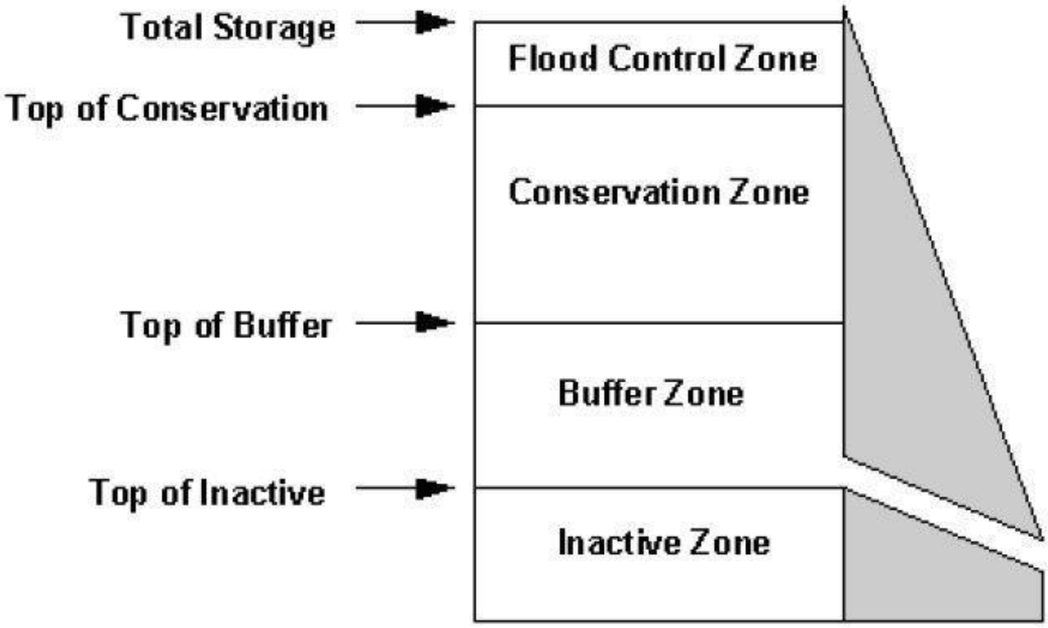


Figure 3.9: Reservoir storage zones used to describe operating rules (source: WEAP User Manual).

The total amount available to be released from the reservoir, Sr is the full amount in the conservation zone, the flood control zone and a fraction (given by bc) of the storage in the buffer zone (Yates et al., 2005).

$$Sr = Sf + Sc + (bc * Sb) \text{ -------------------------------------- } \quad 3.1$$

Where: Sr is total available water that can be released from the reservoir storage, Sf is storage of flood control, Sc is storage of conservation, and bc is the buffer coefficient.

3.8 Hydro-Meteorological data Screening and Analysis

Engineering studies of water resources development and management depend on hydro-meteorological data. These data should be stationary, consistent, and homogeneous when they are used for simulating a hydrologic system.

3.8.1. Meteorological data

Selected twenty three year’s climate data daily rainfall, daily maximum and minimum temperature, relative humidity, wind speed and sunshine hour for selected stations were collected from National Meteorological Service Agency (NMA). Only the Hawassa station has all mentioned climate variables and the other station has with less than two parameters, having more than 2 to 5 years of missing data’s. Therefore, estimation of missing data was done using LocClim V1.10 database, developed by FAO.

The new LocClim program uses a statistical analysis based on data from about 30,000 meteorological stations around the world to estimate climate data for any location (Boke, 2017, Mugatsia, 2010).

3.8.2 Reference Evapotranspiration

Long-term mean values are used as input data for the model. It is thus assumed that the inter-annual variation in evapotranspiration is much more dependent on the soil moisture conditions than on the inter-annual variation in potential evaporation (HMS). For this specific study Penman-Monteith method is adopted to calculate the daily Reference Evapotranspiration (Allen et al., 2000). The calculated average evapotranspiration from Hawassa station is used for model input.

$$ET_0 = \frac{0.408\Delta(\mathrm{Rn} - \mathrm{G}) + \gamma\,\frac{900}{\mathrm{T}+273}\mathrm{U}_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\mathrm{U}_2)} \text{ ---------------- } 3.2$$

Where,

ETo	Reference evapotranspiration [mm day^{-1}],
R_n	Net radiation at the crop surface [MJ m^{-2} day^{-1}],
G	Soil heat flux density [MJ m^{-2} day^{-1}],
T	Mean daily air temperature at 2m height [^{o}C],
U_2	Wind speed at 2m height [ms^{-1}],
e_s	Saturation vapour pressure [kPa],
e_a	Actual vapour pressure [kpa],
e_s - e_a	Saturation vapour pressure deficit [kpa],
Δ	Slope vapour pressure curve [kPa ^{o}C^{-1}],
γ	Psychrometric constant [kPa ^{o}C^{-1}].

In equation 3.2, the value 0.408 converts the net radiation Rn expressed in MJ/m2.day to equivalent evaporation expressed in mm/day.

Table 3.1 Long term average monthly potential evapotranspiration for Hawassa station (1990- 2012)

Months	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Eto (mm/month)	122.0	120.4	132.6	118.7	119.9	108.3	97.6	102.7	102.8	113.0	115.3	118.7

3.8.3 Hydrological Data

The hydrological data is necessary for performance calibration and validation of the model. The hydrological data was received from the Ethiopian MoWIE (Ministry of Water, Irrigation and Electricity) department of hydrology. The hydrological data collected was 23 years (1990-2012) daily flow for model calibration and validation.

The First step before using flow data into model is checking the data using outlier test. Outlier is an observation that deviates significantly from the bulk of the data, which may be due to errors in data collection, or recording or due to natural causes. The presence of outliers in the data causes difficulties when fitting a distribution to the data. Low and high outliers are both possible and have different effects on the analysis (Grubbs and Beck, 1972).

The Grubbs and Beck (1972) test was used to detect the outliers.

$$X_H = exp^{(\bar{x}+K_N \mathrm{S})} \text{ -- } 3.3$$

$$X_L = exp^{(\bar{x}-K_N \mathrm{S})} \text{--- } 3.4$$

Where $\bar{x}$ and S are the mean and standard deviation of the natural logarithms of the sample, X_H is higher outlier and X_L lower outlier respectively.

$$K_N = -3.62201 + 6.28446N^{\frac{1}{4}} - 2.491436N^{\frac{1}{2}} + 0.491436N^{\frac{3}{4}} - 0.037911N \text{ --- } 3.5$$

WhereK_N is the Grubbs and Beck statistic sample sizes and significance levels by Grubbs and Beck (1972) at 10% significant level, where N is the sample size. Sample values greater than X_H are considered to be high outliers while those less than X_L are considered to be low outliers. As observation indicates at dato village gauging station stream flow data is less than X_H=60.72 and greater than X_L=24.96. Therefore, no outliers were detected.

3.9 Lake Hawassa Catchment Simulation

WEAP model was used in this particular study to simulate the hydrologic process of the case study area in the Lake Hawassa catchment. The design of WEAP model made it ideal to use to simulate various climate change scenarios. The components simulated are the Tikurwuha River and Lake Hawassa level.

3.9.1 Tikurwuha River

The rainfall runoff method was used to simulate river flows in this study; this was constrained by the type of data available (Rainfall, ETo and Kc). Data from the surrounding station, located in the catchment, was used to represent the climatic data, i.e., precipitation, and temperature. The range of data is in between 1990 to 2012 at daily scale obtained from National Meteorological Agency (NMA), and the monthly scale data were used to simulate catchment process in WEAP21. The measured river flow data within the same range of years obtained from Ministry of water, irrigation and energy (MWIE). The measured flow data were used to calibrate and validate the WEAP hydrology model.

3.9.2 Lake Hawassa

Lake Hawassa is the terminal lake where the only outflow is through Evaporation. Lake Hawassa was simulated in WEAP as water demand. The supply sources are Tikurwuha River and precipitation on Lake surface area. The required data for simulating the Lake Hawassa are:

1. Storage Capacity
2. Initial Storage
3. Volume Elevation Curve
4. Net Evaporation
5. Observed Volume (for calibration and validation)

The storage capacity of Lake Hawassa is 1364 million cubic meters (MCM) (Dadi, 2013) and initial storage was set as zero, initial storage which was recorded for the first day of January of 1990, in the first month of the Current Account. The other required inflow and outflow data were quantified as below and inject as input data for the model. In order to calculate the amount of evaporation and/or the amount of energy production from hydropower, WEAP must have a function to convert between volume and elevation. This function is defined by the points on the Volume-Elevation Curve. For this study, the area, volume and elevation curve were used on the basis of the lake bathymetry reported by W.W.D.S.E (2000).

The monthly flow at the Lake is calculated by using the area ratio method. The delineated Lake catchment area using Arc GIS software, from the 30 x 30digital elevation model reveals that the area covers, 1200 km^2 and that of the area of the Tikurwuha gauging station covers 625 km^2, hence by assuming the two areas have similar catchment characteristics and climatic condition, the catchment inflow to lake is found by multiplying runoff at the gauging station by their area ratio of 1.92.

3.9.3 Lake Evaporation

Because Lake Evaporation cannot be measured directly, it should be determined indirectly by one or more of several methods, such as water balance, energy balance, Penman–Monteith's formula, pan evaporation technique and so on.

For the present study, the Penman–Monteith method was selected to determine the monthly evaporation rates.

Open water evaporation was calculated by using the FAO CROPWAT Version 4.3 program which uses the Penman-Monteith method and then applies an aridity correction factor. The CROPWAT program was developed to estimate potential evapotranspiration (PET) or ETo which is also defined as reference evapotranspiration (FAO, 1998). According to FAO Irrigation and Drainage Paper 56, page 114, the conversion of ETo to evaporation of open water, with depth higher than 5 m, clear of turbidity, in temperate climate, would be varied between 0.65 and 1.25.

Finally to introduce Evaporation from Lake Surface area in WEAP model, the Net monthly Evaporation rate is calculated in such that Evaporation minus Precipitation on lake surface area. The monthly evaporation rate can be positive or negative to account for the difference between evaporation and precipitation on the lake surface area. A positive (negative) net evaporation represents a net loss from (gain to) the lake (Sieber and Purkey, 2015).

3.10 WEAP Model Calibration

The calibration of an integrated river basin model, such as WEAP, is a challenging process. In general, calibration is process of adjusting the parameters of the models to appropriately mimic the historical observations. The process of model calibration is done either manually or by computer-based automatic procedures. The goodness-of-fit of calibrated model is basically based on good water balance and a good overall agreement of the shape of the hydrograph by comparing the simulated and observed hydrographs. For an experienced hydrologist it is possible to obtain a very good and hydrological sound model using manual calibration. In automatic calibration, parameters adjusted automatically according to a specified search scheme and numerical measures of the goodness-of-fit. As compared to manual calibration, automatic calibration is fast, and the confidence of the model simulation can be explicitly stated.

WEAP includes a linkage to a parameter estimation tool (PEST) that allows the user to automate the process of comparing WEAP outputs to historical observations and modifying model parameters to improve its accuracy.

In addition to comparing the simulated and observed time series the performance of the model must be evaluated for the extent of its accuracy (Goswami et al., 2005). Hence, for this study, the model performance in simulating observed discharge was evaluated during calibration and validation by; Inspecting simulated and observed runoff graphs visually by calculating Nash and Sutcliffe efficiency criteria (NSE) (commonly used in hydrological modelling). The Nash and Sutcliffe coefficient is a measure of efficiency that relates the goodness-of-fit of the model to the variance of measured data. NSE can range from - ∞ to 1 and an efficiency of 1 indicates a perfect match between observed and simulated discharges. NSE value between 0.9 and 1 indicate that the model performs very well while values between 0.6 and 0.9 indicate the model performs well (Goswami et al., 2005). The largest disadvantage of this efficiency criterion is that larger value in a time series are strongly overestimated whereas lower values are of minor importance. For the quantification of runoff prediction this leads to an overestimation of model performance during peak flows and underestimation during low flow conditions. The calibrated flow of Tikurwuha River is injected as head flow to the river segment in WEAP model to simulate the lake level.

$$NS = 1 - \frac{\sum_{i=1}^{n}(Qsim{,}i - Qobs{,}i)^2}{\sum_{i=1}^{n}(\mathrm{Qobs{,}i} - \overline{\mathrm{Qobs}})^2} \text{ --------------------------------- } 3.6$$

Where,

Q obs	Observed flow,
Q sim	Simulated flow and
$\overline{Q}obs$,	Average of observed flow

3.11 Hypothetical Scenario

Scenarios are self-consistent story-lines of how a future system will respond to different conditions (e.g., new policies, population change, climate change, new technologies). The simulated results from the scenarios are compared against a reference scenario to assess their impacts on the water system. All scenarios inherit data from the Current Accounts year reference period. The scenarios can address a broad range of "what if" questions, such as: What if climate change alters the hydrology? What if population growth and economic development patterns change? What if reservoir operating rules are altered? What if groundwater is more fully exploited? What if water conservation is introduced? What if ecosystem requirements are tightened? What if new sources of water pollution are added? What if a water recycling program is implemented (Sieber and Purkey, 2015).

For this study, Hypothetical scenario is applied by increasing and decreasing the precipitation in plausible amount and increasing the temperature from the baseline temperature, for the purpose of examining the response of the catchment and lake level for different climatic scenario. All scenarios was built and analysed for the period 2013 to 2035 on the basis of the output from the MAGICC/SCENGEN (Model for the Assessment of Greenhouse-gas Induced Climate Change) / (Regional and global Climate SCENario GENerator) coupled model (Version 4.1) in the work of Climate projections for Ethiopia (NMA, 2007, USAID, 2012). The following table shows the incremental scenario adopted by this study for the analysis of climate change impact on the lake catchment.

Table 3.2 Adopted incremental scenario

Scenarios	S1	S2	S3	S4	S5	S6
Temp. (^oC)	+ 1.25	+ 1.25	+1.25	+ 1.1	+ 1.1	+ 1.1
Precp. %	- 20%	- 10%	0	+10%	+20%	0

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Introduction

This chapter presents the result of climate change impacts and the analysis of scenarios in the Lake Hawassa catchment using the application of WEAP21. For this particular study, two hypothetical scenarios by changing demand and supply side by certain percentage where made and each scenario is evaluated based on the reference scenario.

4.2. Tikurwuha River and Lake Hawassa Model Calibration Results

Calibration of the model means adjusting some parameters where there is good match between the simulated and observed data at the selected stations. Calibration of stream-flow and lake are necessary to make sure that the WEAP model is correctly representing the current situation in the study area. For this purpose, observed data is required for calibration of the model as sufficiently long continuous observed data is not available for any site in the catchment. Calibration of the WEAP model was based on the flow at the gauging stations at Nr. Dato village and it was done for the period 1990-2011 and the Lake level at Hawassa station for the period 1992 to 2011. Because, the WEAP simulation results entirely depend on the quality of the input data including river discharge, groundwater recharge, urban and agricultural demands (Holger et al., 2011).

The accuracy of the model is assessed by simulated and observed stream flow and lake level. As the results from figures 4.1 and 4.2 below indicates, it can be observed that the simulated and observed data are comparable in Tikurwuha River and Hawassa Lake level. The result shows that there is strong association between simulated and observed values where the mean NSE values are 0.93 and 0.9 respectively.

An observed and simulated flow and Lake level of the current situation data displayed by the graph shows that the simulated is fitting well in the observed data and the model performance are perfect and provides a good estimate. The model performance indicates that it is possible to predict the general trend of the catchment processes though this result was obtained after variation of model parameters.

The goal of calibrating the watershed rainfall runoff model in WEAP was not to exactly represent the true runoff properties of the existing watershed but rather to develop a good representation of the existing stream-flow that could serve as a base condition for the climate change analysis. By adjusting and modifying the parameters of land use factors crop coefficient (Kc) along with Effective precipitation the model was able to get reasonably good match to the observed samples.

For assessing the climate change impact, it is assumed that, the basic characteristics of the watershed (the land-use) will not change for the projected period of 2035. Thus, in calibrating the WEAP model a set of characteristics for the catchment have been selected and there is further assumption that the rainfall-runoff processes will stay reasonably constant under changing precipitation and temperature conditions in scenario evaluation. While changing temperature and precipitation conditions will influence the runoff simulation through increased evapotranspiration and additional assumption is made as the catchment runoff characteristics will not change as a result of climate change.

Figure 4.1 shows the time series and where Qo is the observed stream flows and Qm is the simulated stream-flow for the reference scenario. The trend of simulated flow is reasonably close to the trend of observed stream-flow and both the calibration and validation periods show a similar fit to the data.

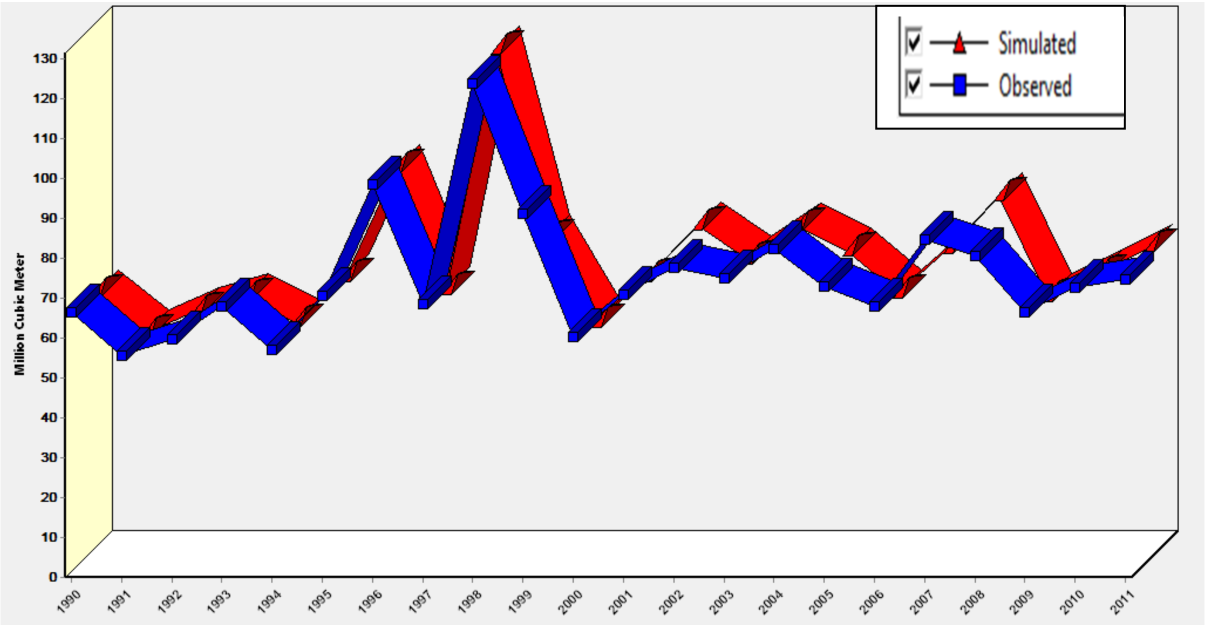


Figure 4.1: observed and simulated Tikurwuha River

For calibration of the Lake storage assumption about how the Lake will operate using the zones was made. The operating zones were based on the information provided by online WEAP forum (the buffer zone and inactive zone) is set equal to the initial storage at the beginning of the simulation period and it is assumed that these zones will not change over the projected period up to 2035.

Figure 4.2 show the simulated Lake level follows the observed trend reasonably well both for the calibration and validation periods.

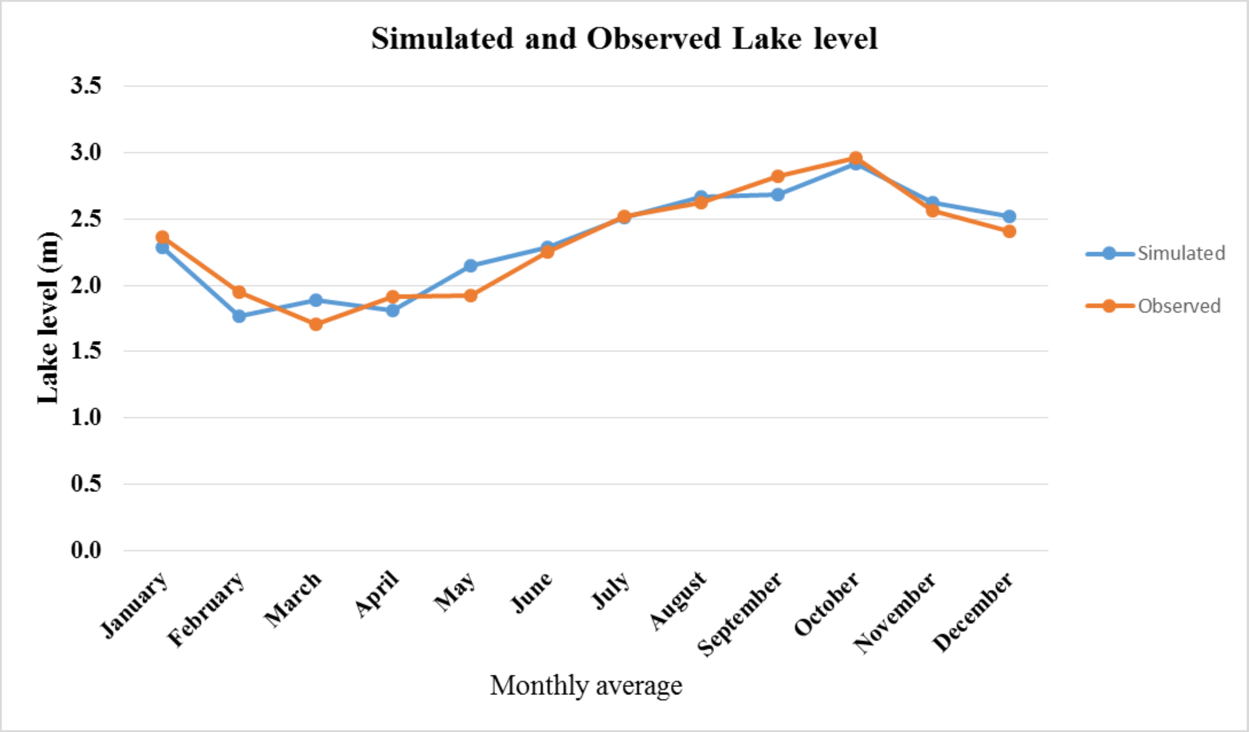


Figure 4.2: Observed and simulated Lake Level

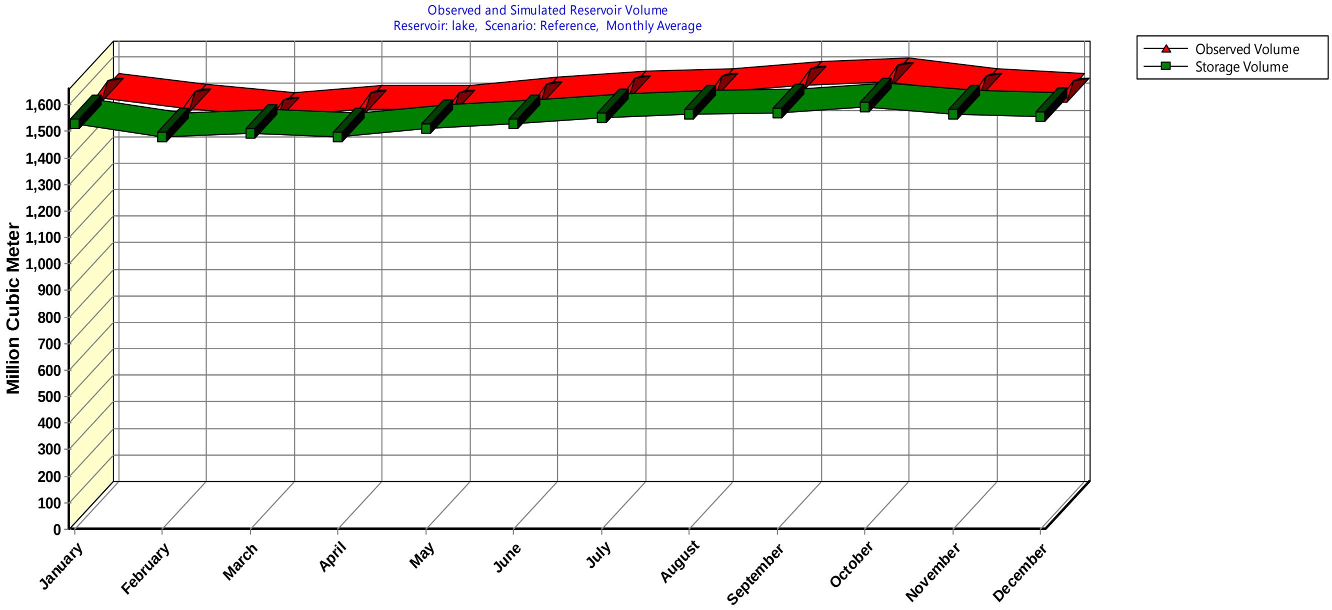


Figure 4.3: Average Monthly Simulated and Observed Lake Volume

To make the projections of the impact of climate change to the year 2035, the study attempts to create a platform of what the current operation is and then estimate how the catchment and the lake would respond to it within different temperature and precipitation in the future conditions. Here, the study is not predicting about the future climate change but rather assessing how it would be altered in a future with hypothetical scenario by changing both temperature and precipitation from the baseline scenario.

Overall the calibration of the existing situation in terms of stream-flow and Lake Level is reasonable and therefore, it was assumed that for the purpose of this study, the reservoir operation would follow these operational zones and the zones would not change over the projected scenario to the year 2035.

4.3 Scenarios

In this study, much emphasis has been given to the water stored in Lake Hawassa and scenarios have been developed for 23 years where the year 2012 was considered as initial condition. As a result, the following two scenarios have been considered:

a) Reference scenario- *where no change occurs related to climate change*, and
b) Climate change scenario.

In both scenarios, the question provided for the model states: How does the Lake Hawassa catchment behave in different climatic circumstances?

4.4 Hypothetical Scenarios

For the climate change scenario, the use of the output from the MAGICC/SCENGEN (Model for the Assessment of Greenhouse-gas Induced Climate Change) / (Regional and global Climate SCENario GENerator) coupled model (Version 4.1) in the work of Climate projections for Ethiopia was taken as a baseline which indicates that under mid-range climate change drivers (IPCC A1B scenario), (NMA, 2007) by the year 2060. The result from these model reveals that as the mean annual temperature will increase in the range of 0.9 -2.1 °C, precipitation could fall by 10% to20% and to an increase of 24% compared to the 1970-1999 normal (USAID, 2012).

Based on the above results, two climate change scenarios have been simulated for this study by shifting the rainfall and maximum and minimum temperatures northward and southward of the present 1990-2012 situation. The scenario developed was: a) *a drier period*- by a shift of temperature 1.25^{o}C northwards and precipitation 10% to 20% southwards; and b) *a wetter period*- by a shift of temperature 1.1^{o}C northwards and precipitation 20% northwards.

To apply these climate scenarios to the WEAP model, the changes in climatic variables are provided on a monthly basis and these changes was applied on a monthly basis. In order to simulate the hydrologic responses of the catchment these changes were added or subtracted from each month of the reference year up to the year 2035.

4.5 Scenario Evaluation

Scenario evaluation allows decision makers and water managers to answer “what if” questions related to water systems. The reference scenario, based on the Current Account, is the base scenario and the other scenarios are based on the reference scenario by varying the supply and/or demands. In this case, the simulations were actually made beginning from 2012 where the first year of the simulation were used for model warm-up and were not shown in the model results.

4.5.1 Scenario One: Impact of the Extended Dry Scenario

Scenario one is based on a shift of temperature 1.25^{o}C northwards and precipitation 10% southwards from the observed monthly average. The impact of scenario one was modelled in the study area and the results are compared to stream-flows and storage levels in Lake Hawassa with the current (1992-2011) mean monthly as shown below on Figure 4.4 and 4.5

Figure 4.4 show that relative to the current condition the simulated future inflow shows an average annual decrease in volume by 12% in 2035s where the average annual absolute change in temperature reveals an increase amount by 1.25^{o}C and the precipitation shows a decline by 10%. There are various reasons why decreasing stream-flow would be expected.

The first reason is that temperature is increasing resulting in increasing evapotranspiration by crops, and therefore the soil will be dried more and sooner. Another reason is that the amount of precipitation is being decreased due to increasing temperature. In this situation much of the precipitation will be infiltrated into the soil, which is drier due to high temperature and evapotranspiration. Therefore the combination of all these processes can be lead to less available runoff.

Figure 4.5 shows that the Lake storage will decrease significantly. This is because of increasing temperature and decreasing precipitation. Obviously, the amount of inflow to the lake is decreasing and the net evaporation from the lake would increase due to increasing temperature.

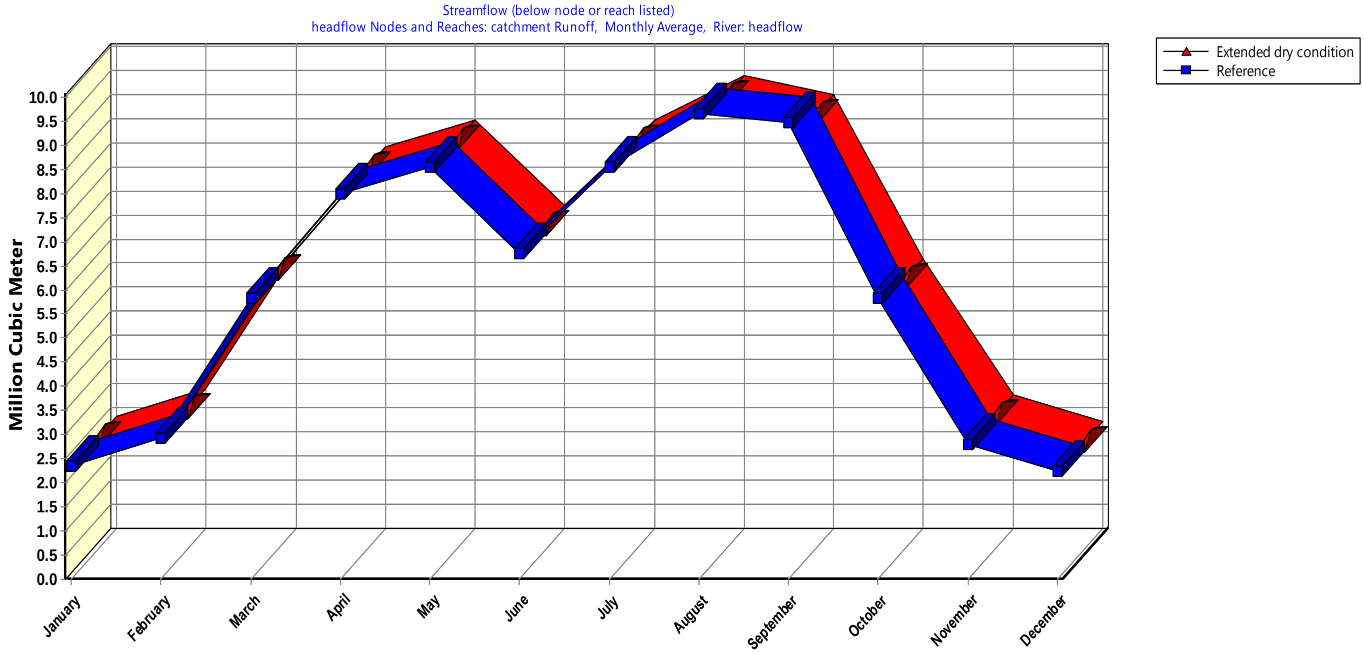


Figure 4.4: Modelled average monthly stream-flow based on scenario one

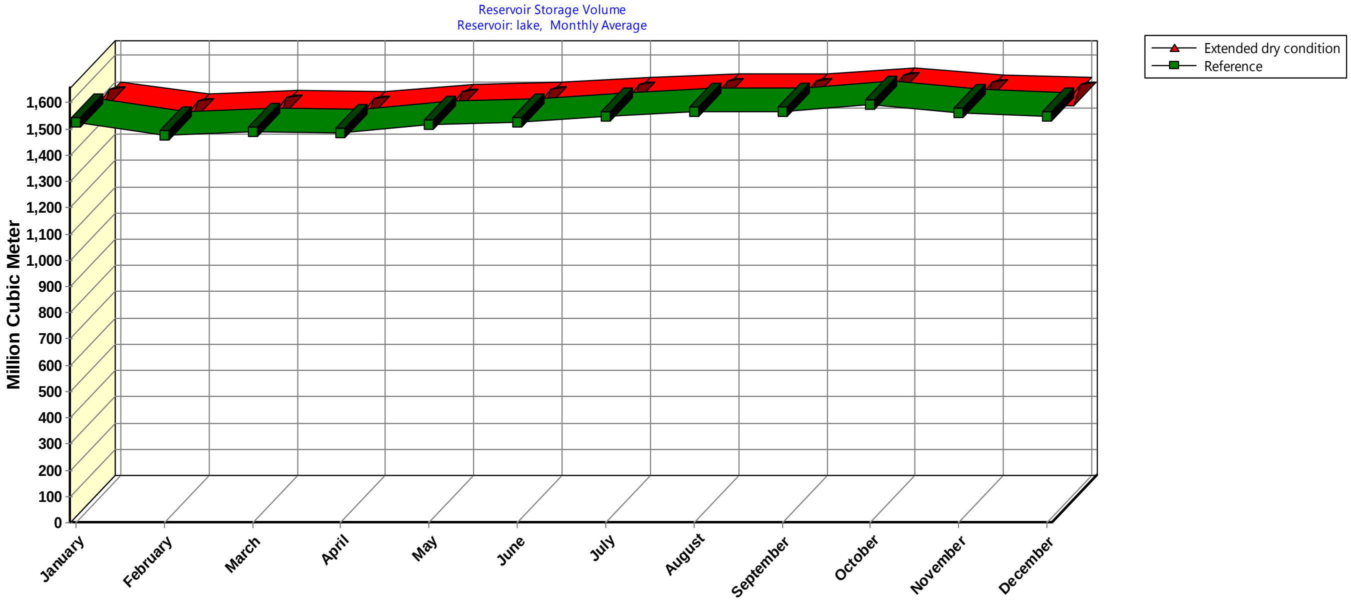


Figure 4.5: Modelled average monthly Lake storage based on scenario one

4.5.2 Scenario Two: Impact of Extended Wet Scenario

Scenario two is based on a shift of temperature 1.1°C northwards and precipitation 20% northwards from the observed monthly average. Figure 4.6 and 4.7 below shows the impacts of scenario two on the catchment and Lake. In this scenario it is expected that the average annual volume of inflow will increase by 12% where the average annual absolute change in temperature reveals an increase amount by 1.1 °C and the precipitation shows an increase in 20%. So the trend of increasing stream-flow stays relatively similar to the reference scenario. Although the inflow into the Lake is increasing, the volume of stored water stays relatively similar to the reference scenario.

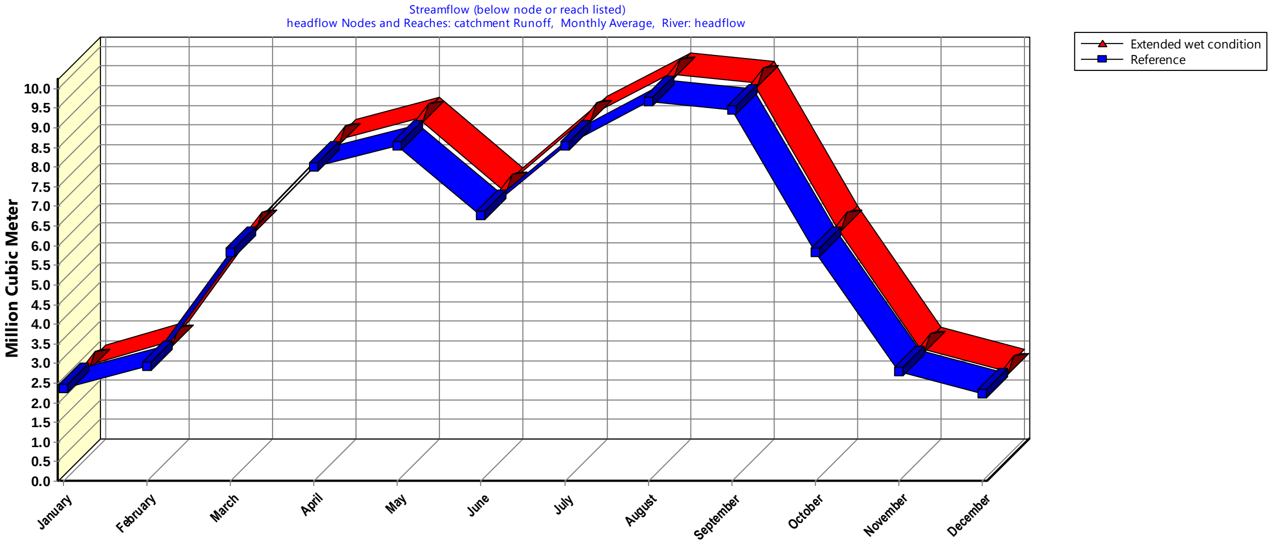


Figure 4.6: Modelled average monthly stream-flow based on scenario two

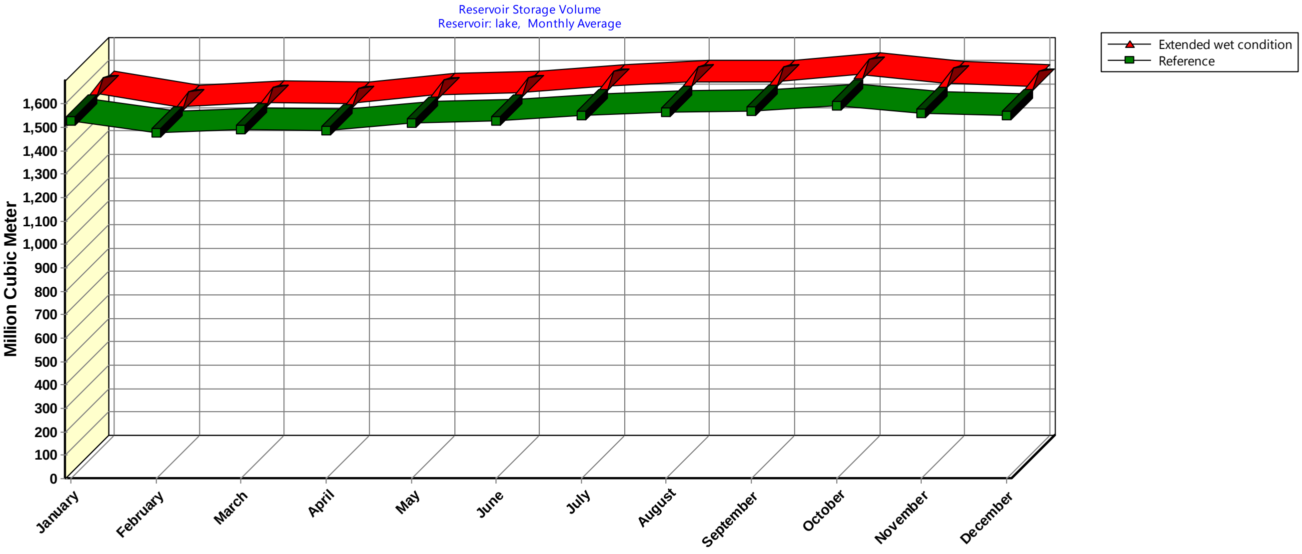


Figure 4.7: Modelled average monthly Lake Storage based on scenario two

Generally, the evaluation of scenario under climatic change on Lake Hawassa catchment for the study period (2013-2035) shows that there is considerable shift in some of these parameters. When the mean annual temperature increases the precipitation shows an increasing and a declining trend in the second and first scenarios respectively. As a result, the effect of this climate change could greatly affect the hydrological system of the catchment. Then, given these circumstances, less water reaches the Lake (in the first scenario) and more water reaches the Lake (in the second scenario). In conclusion, the evaluation of the climate change impact on Lake level fluctuations was modelled with Dry and Wet scenario where the result of the scenarios indicate that the Lake level will reach 3.6m below and 3.72m higher than the observed level respectively by 2035. Besides, a similar comparison using volumetric values of the Lake reveals that the Lake storage decline by 366.7 million cubic meters and an increase of about 366.84 million cubic meters will occur in the same year.

Besides, the finding of this study shows that, apart from other parameters like climate change, the decline of catchment Land use/Land cover and rapid urbanization has a considerable influence on the level of the lake. Therefore, as a possible response to this problem effective integrated management and planning mechanisms needs to be implemented on Lake catchment for better and sustainable utilization of the Lake.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study, WEAP model were used to simulate catchment hydrologic process, Lake Water balance, and evaluate the potential impacts of climate change on catchment responses and lake level of Lake Hawassa catchment. The WEAP model was calibrated to an existing data set for the Tikurwuha River and Lake Hawassa level. Besides, hypothetical scenarios were simulated to determine the impacts of climate change on lake level fluctuation for the period of 2013 to 2035.

Based on the finding of this study, the following conclusions are drawn;

1. Software platforms have distinguished characteristics of serving the purpose of different objectives that helps to understand the main purpose of developed software and to have a clear judgment on which one it fits appropriately in the individuals’ case studies.

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

3. The WEAP model was calibrated using streamflow and Lake Level for the period of 1990 to 2011. The results of calibration indicated the streamflow and Lake level were simulated reasonably with the model performance criteria of Nash and Sutcliffe values 0.93 and 0.9 respectively. This justifies that WEAP is more appropriate hydrological model for this specific study in order to generate the inflow and simulate the Lake level at future climatic condition.

4. In order to evaluate the climate change impact on catchment by simulating the model, it was assumed that the basic characteristics of the catchment will not change for the projected period of analysis whereas the rainfall-runoff processes will stay reasonably constant under changing precipitation and temperature conditions. These assumptions allow the separation of the impacts of climate change from other potential changes in the system though not generalized.

5. The results of these projections using the modelling framework indicates that, evaluation of the climate changes impact on Lake level fluctuations with Dry and Wet scenario the Lake level will reach 3.6m below and 3.72m higher than the observed level respectively by 2035.

6. The finding of this study also shows that, apart from other parameters like climate change, the decline of catchment Land use/Land cover and rapid urbanization has a considerable influence on the level of the lake. Therefore, as a possible response to this problem effective integrated management and planning mechanisms needs to be implemented on Lake Catchment.
7. Besides, as the finding reveals, the Lake level is more sensitive to precipitation than temperature change in the future compared to current (1990-2011) condition.
8. Generally, the study illustrates the value of scenarios provide insight for integrated water resource planning that can support the possible remedial measures for better management of the Lake for the future and sustainable use.

5.2 Recommendation

Subsequent to the finding and conclusions aforementioned, the following main recommendations can be forwarded for the purpose of this specific study;

- ✓ Improving the current data availability will improve the model accuracy to evidently show the relationships among the variables.
- ✓ It will be a valuable asset for this model to have more stream gauge stations to collect a complete set of monthly variable that include: precipitation, temperature, wind, land use, Lake evaporation and lake bathymetric map.
- ✓ Further development and refinement of coupled Climate and WEAP models is recommended as conclusion rather on being hypothetical.
- ✓ The relevant stakeholders need to develop a more integrated water resource planning and management mechanism which in turn allows a better and sustainable utilization of the Lake.

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APPENDICES

Appendix A: Meteorological data of Hawassa Station

Appendix A.1: Monthly Rain fall at Hawassa station (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	11.11	93.7	121.1	89.9	85.3	44.4	139.5	39.5	94.1	27.3	7.6	3.8	757.31
1991	12.3	90.6	87.4	48	129.5	116.7	109.2	90.6	104	21.6	12.2	44.8	866.9
1992	23.4	83.5	73	109	60.5	83	92.8	123.6	74.5	142.3	80.1	16.6	962.3
1993	101.6	109.1	22.3	104.9	165.3	46.7	54.7	130.8	47.8	130.8	10.5	3.9	928.4
1994	0	4.7	56.8	108.7	80.8	146.2	195.7	118.9	68.9	58.8	19.1	2.9	861.5
1995	0.8	21.4	61.8	156.1	43.6	118.7	175.7	134.7	166.8	22.3	18.3	84.2	1004.4
1996	78.4	36.9	89.6	113.8	161.5	243.3	121.2	108.7	145	69.6	19.7	1.4	1189.1
1997	23.4	1.7	75.1	125	73	111.2	98.6	113.9	118.9	157.1	132.2	24	1054.1
1998	92	140	90.8	86.4	88.4	56	172.9	108.3	109.6	193.3	10.6	0	1148.3
1999	19.8	0.4	105.5	27.1	64.7	99.8	135.1	83.8	115.4	120.4	20.1	16.8	808.9
2000	1.1	0	11	132	145.1	36.4	80	179.3	87.6	110.7	29	9.3	821.5
2001	1.8	39.9	122.7	67.2	233.7	137.5	93.4	131.7	89.7	80.2	2.6	21.3	1021.7
2002	52.5	2.4	128.7	119.6	85.2	91.9	76.6	190.4	83.2	37.3	0	51.5	919.3
2003	30.4	2	78.2	179.1	40.4	110.5	74.5	76.1	85.5	53.4	6.2	152.6	888.9
2004	46.2	94.2	42	83.1	81.5	75.7	75.4	117.1	116	57.1	94.2	15.2	897.7
2005	81.1	7.7	120.9	156	144.5	73.2	150.9	61.3	122.2	28.4	46	10.4	1002.6
2006	1.7	12.01	139.2	145.9	74.4	108	171.1	169.3	194.9	56.9	79.2	48.3	1200.91
2007	18	56	70.4	112	166.1	225.4	129.1	105.1	233.8	33.1	3.7	0	1152.7
2008	33.7	7.5	3.4	57.8	121.4	118.2	120.5	123.5	160	66.1	97.1	5.8	915
2009	32.8	9	60.3	45.6	103.1	51.6	92	112	81.7	41.6	4.1	69.9	703.7
2010	26.6	58.4	124.5	96.1	173.5	52.9	132.5	136.6	96.1	47.1	32	56	1032.3
2011	2.3	7.1	55.5	73.7	193.6	65.5	150.8	155	125.5	5.5	88.2	0.2	922.9
2012	0	2.4	13	210.5	91.3	89.8	161.01	87.2	86.8	15.2	23.2	13.1	793.51

Appendix A.2: Monthly Average Air Temperature at Hawassa station (^{o}C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	18.8	20.9	20.1	21.0	20.3	19.7	19.3	19.1	19.4	19.3	20.2	19.1	19.8
1991	21.1	20.8	21.1	21.0	20.9	20.6	18.8	19.4	19.5	18.7	19.3	18.9	20.0
1992	20.5	21.0	21.7	22.0	20.4	20.1	19.1	19.3	18.8	19.4	18.8	19.8	20.1
1993	19.8	19.6	20.3	21.0	20.5	19.6	19.4	19.3	19.3	19.8	19.7	19.5	19.8
1994	20.1	21.6	21.9	21.6	20.5	19.6	18.9	19.6	20.1	19.2	19.1	19.1	20.1
1995	20.1	21.7	21.8	21.1	20.6	20.3	19.3	19.6	19.4	19.9	18.8	19.9	20.2
1996	20.2	20.7	21.2	20.8	20.4	19.2	19.2	19.4	19.4	19.0	18.5	19.1	19.8
1997	20.7	20.1	22.0	20.4	20.3	19.7	19.0	19.9	20.0	20.1	20.1	19.3	20.1
1998	20.6	21.6	21.9	22.2	21.5	20.5	20.0	19.9	20.0	19.9	18.2	18.0	20.3
1999	19.7	20.7	21.0	20.8	20.4	20.1	19.0	19.3	19.7	19.5	18.2	18.7	19.7
2000	19.5	20.7	21.5	21.5	20.1	19.7	19.5	19.4	19.3	19.8	18.8	19.0	19.9
2001	20.1	20.8	21.2	21.4	20.5	19.7	19.6	19.7	19.5	20.3	19.3	19.9	20.2
2002	20.3	21.4	21.4	21.0	21.2	20.1	20.3	19.8	19.7	20.5	19.8	20.8	20.5
2003	20.1	21.4	21.9	21.2	21.2	19.9	19.4	19.7	20.0	20.1	20.2	18.9	20.3
2004	20.9	20.2	21.2	21.0	20.9	19.9	19.7	19.9	19.5	19.1	20.1	20.0	20.2
2005	20.1	21.5	21.9	21.7	20.4	20.1	19.4	20.2	20.2	20.2	18.8	18.1	20.2
2006	21.0	21.8	21.6	21.0	20.8	20.3	19.7	19.7	19.9	20.4	19.5	20.0	20.4
2007	20.6	21.1	21.3	21.2	21.3	20.1	19.7	19.5	19.7	18.9	19.3	18.4	20.1
2008	20.0	20.6	21.5	21.7	20.4	20.0	19.5	19.6	19.9	19.7	18.8	19.0	20.1
2009	20.1	21.2	22.1	21.8	21.7	20.7	20.1	20.3	20.5	20.5	20.1	20.7	20.8
2010	20.8	21.7	21.2	21.8	21.6	20.7	19.8	20.2	19.8	20.6	19.9	19.6	20.6
2011	20.7	21.2	21.8	22.4	21.4	20.8	20.1	19.7	20.0	20.3	20.4	18.8	20.6
2012	20.0	21.2	22.6	21.5	21.3	20.8	20.0	20.0	19.8	20.0	20.7	20.2	20.7

Appendix A.3: Monthly Relative Humidity at Hawassa station (%)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	59.2	69.8	72.2	70.4	71.3	68.8	72.9	74.6	72.9	63.0	56.7	51.2	66.9
1991	53.6	63.2	68.2	66.7	70.8	67.9	76.7	75.3	75.7	62.6	52.8	58.2	66.0
1992	60.6	67.1	60.0	63.1	70.9	70.5	75.1	76.9	77.2	74.1	64.3	63.3	68.6
1993	67.0	70.1	55.0	71.3	74.8	74.8	74.5	73.6	74.2	72.5	57.2	52.6	68.1
1994	50.1	48.8	60.4	66.0	74.7	74.5	79.0	77.5	74.6	63.6	61.6	55.1	65.6
1995	50.5	56.3	64.1	74.1	71.9	70.9	75.9	76.5	76.3	66.8	58.1	61.9	67.0
1996	66.0	54.8	68.1	72.6	77.1	78.6	78.8	78.8	78.7	67.5	59.1	54.2	69.6
1997	60.2	46.2	55.8	73.3	70.6	75.0	75.4	70.8	71.2	71.5	70.5	62.7	67.0
1998	69.5	65.7	66.4	63.0	71.0	68.6	74.9	75.1	73.2	75.0	57.5	51.4	67.6
1999	54.9	44.2	66.1	63.4	69.6	69.8	75.8	74.8	74.2	75.3	57.7	55.0	65.2
2000	48.5	45.1	46.9	62.6	73.7	70.8	75.8	73.4	77.8	75.2	64.8	59.1	64.5
2001	57.0	55.5	66.7	69.0	72.5	74.3	74.9	75.4	75.5	70.5	54.2	53.7	66.7
2002	59.5	47.2	66.2	63.6	71.1	71.3	67.6	72.9	72.7	64.4	49.1	64.1	64.3
2003	59.5	51.2	59.8	68.6	68.0	72.4	77.0	77.0	73.6	63.8	56.4	59.6	65.7
2004	62.0	56.2	54.7	72.7	68.3	69.6	70.0	73.1	76.1	64.1	57.5	57.8	65.2
2005	57.9	48.9	62.7	62.9	77.2	73.0	74.0	71.4	74.6	66.8	57.2	48.5	64.7
2006	52.0	54.6	62.6	72.1	70.9	72.6	76.1	79.1	76.8	74.2	63.4	66.9	68.5
2007	62.0	61.7	57.3	71.1	73.7	76.4	75.5	79.1	78.8	65.5	58.7	53.0	67.7
2008	54.7	49.1	42.9	61.6	73.8	72.9	76.2	76.8	77.5	69.5	64.2	54.0	64.5
2009	58.2	52.4	53.6	67.1	66.6	68.6	70.4	72.9	73.1	66.8	46.2	63.2	63.3
2010	59.1	66.4	67.1	71.7	75.8	72.9	76.3	76.3	77.0	65.6	56.2	54.9	68.3
2011	54.6	49.6	55.4	60.6	75.5	76.3	77.3	77.8	79.2	65.4	68.5	59.6	66.7
2012	54.8	49.0	45.6	71.3	69.9	69.6	78.2	75.2	79.6	65.7	58.7	54.8	64.4

Appendix A.4: Average Wind Speed at Hawassa station (m/s)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	1.00	1.06	0.86	0.87	1.07	1.41	1.28	1.05	0.93	0.77	0.76	0.94	1.00
1991	1.00	1.06	0.86	0.87	1.07	1.41	1.28	1.05	0.93	0.77	0.76	0.94	1.00
1992	1.00	1.05	0.86	0.87	1.07	1.41	1.28	1.05	0.93	0.77	0.76	0.94	1.00
1993	1.00	1.06	0.86	0.87	1.07	1.41	1.28	1.05	0.79	0.54	0.74	0.93	0.97
1994	1.05	1.07	0.99	0.83	0.81	1.11	0.81	0.94	0.66	0.58	0.71	0.94	0.87
1995	0.90	0.90	2.36	0.78	0.89	1.24	0.96	0.88	0.68	0.65	0.55	0.71	0.96
1996	0.86	0.79	0.78	0.75	0.73	0.98	0.99	0.76	0.67	0.53	0.62	0.75	0.77
1997	0.80	1.03	0.91	0.69	0.84	0.93	0.95	0.86	0.67	0.53	0.49	0.65	0.78
1998	0.60	0.56	0.60	0.69	0.79	1.11	1.02	0.97	0.68	0.47	0.50	0.65	0.72
1999	0.75	0.75	0.65	0.76	0.97	1.08	0.96	0.87	0.72	0.56	0.66	0.79	0.79
2000	0.92	0.96	0.83	0.82	0.81	1.18	0.95	0.93	0.67	0.55	0.59	0.67	0.82
2001	0.82	0.73	0.67	0.88	0.77	0.90	0.86	0.79	0.57	0.54	0.62	0.66	0.73
2002	0.76	0.83	0.59	0.66	0.98	1.07	1.06	1.12	0.61	0.58	0.69	0.75	0.81
2003	0.74	0.83	0.82	0.63	0.76	1.01	0.86	0.86	0.72	0.56	0.79	0.78	0.78
2004	0.60	0.56	0.68	0.66	0.89	0.99	0.99	0.76	0.61	0.66	0.72	0.74	0.74
2005	0.72	0.81	0.70	0.72	0.61	1.08	1.01	1.15	0.83	0.65	0.68	0.96	0.83
2006	0.95	0.84	0.73	0.63	0.75	0.93	0.89	0.97	0.87	0.74	0.80	0.85	0.83
2007	1.00	0.83	0.82	0.81	0.94	1.07	0.98	0.98	0.84	0.65	0.87	0.93	0.89
2008	0.85	1.06	0.93	0.98	1.06	1.11	0.96	0.88	0.72	0.67	0.75	0.85	0.90
2009	0.84	0.92	0.84	0.80	1.00	1.01	0.99	0.99	0.75	0.76	0.80	0.74	0.87
2010	0.80	0.77	0.84	0.72	0.84	1.04	0.93	0.88	0.75	0.65	0.64	0.68	0.80
2011	0.68	0.71	0.74	0.65	0.69	0.79	0.69	0.65	0.57	0.56	0.51	0.62	0.66
2012	0.60	0.75	0.73	0.55	0.60	0.79	0.69	0.65	0.57	0.56	0.51	0.62	0.64

Appendix A.5: Sun-shine hours at Hawassa station (hrs)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	8.8	6.0	7.3	6.5	6.5	7.3	5.0	4.5	5.5	8.0	8.6	9.3	6.9
1991	8.4	7.3	7.1	7.4	7.3	6.5	3.7	4.1	5.9	7.6	9.2	8.3	6.9
1992	7.8	7.5	8.2	8.1	7.9	7.0	5.3	4.2	5.5	6.6	8.7	8.7	7.1
1993	7.7	7.2	8.9	6.4	6.9	6.0	4.5	5.3	5.3	6.6	8.1	8.4	6.8
1994	7.7	9.2	7.6	6.6	7.2	6.0	4.4	5.4	5.4	7.7	8.6	9.9	7.1
1995	9.7	7.8	7.2	6.2	8.2	8.3	4.0	5.2	6.7	6.9	9.7	8.8	7.4
1996	8.2	9.2	7.6	6.8	7.3	4.9	4.2	4.8	5.7	8.4	9.4	10.2	7.2
1997	8.3	10.2	8.3	6.5	8.2	6.9	5.7	6.7	7.4	7.1	7.0	8.7	7.6
1998	7.0	8.3	7.8	7.8	6.9	6.5	4.6	4.5	5.3	5.3	9.5	10.1	7.0
1999	9.5	9.9	6.9	7.2	7.9	7.7	4.5	6.2	6.5	5.2	9.3	10.1	7.6
2000	10.1	9.8	9.0	7.2	7.7	7.1	5.1	5.0	5.5	6.3	9.2	9.4	7.6
2001	8.9	9.3	6.4	7.2	7.5	6.1	5.4	5.4	6.6	7.1	9.4	9.7	7.4
2002	9.2	9.7	7.3	7.9	7.3	6.3	6.5	5.9	6.8	7.3	9.8	8.1	7.7
2003	9.0	9.6	8.5	6.8	8.0	7.3	4.2	5.0	6.4	8.7	9.0	9.5	7.6
2004	8.5	9.5	8.5	6.3	8.7	6.3	4.9	5.5	5.4	7.6	8.8	9.5	7.4
2005	9.2	9.5	7.9	7.8	5.8	6.7	4.8	6.8	5.8	7.1	8.9	10.5	7.6
2006	9.2	8.7	7.4	6.6	7.9	6.2	4.8	4.7	4.8	5.9	9.2	8.6	7.0
2007	9.1	9.3	8.4	6.8	7.1	5.4	5.3	4.7	5.0	7.8	9.2	10.3	7.4
2008	9.7	9.4	9.7	6.6	6.9	6.4	4.6	5.3	5.3	6.6	9.2	10.2	7.5
2009	8.7	9.5	9.2	7.1	7.9	8.2	6.0	6.5	5.8	7.7	9.3	7.5	7.8
2010	8.9	6.2	7.5	6.2	6.5	7.1	4.0	4.8	5.4	7.8	9.3	9.1	6.9
2011	9.5	9.5	8.2	7.7	6.0	5.7	4.7	5.2	5.2	8.2	8.0	10.0	7.3
2012	10.2	9.7	8.3	6.2	7.7	6.7	4.0	4.6	5.1	8.0	8.8	9.6	7.4

Appendix B: Hydrological data of Hawassa Station

Appendix B.1: Monthly flow of Tikurwuha River at Dato Village (m^3/s)

Drainage Area 625km^2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	1.46	1.36	2.9	5.29	3.51	1.91	1.85	2.63	2.87	5.9	4.32	1.13	35.13
1991	0.84	0.6	0.45	1.22	3.52	1.33	2.5	3.7	4.51	5.15	3.44	1.97	29.23
1992	0.78	0.3	0.23	0.32	1.14	1.64	2.16	2.97	6.48	8.03	5.59	1.86	31.5
1993	1.09	0.76	0.5	0.42	1.42	3.63	4.44	4.29	5.02	5.9	4.51	3.81	35.79
1994	2.17	0.66	0.34	0.63	1	1.68	2.82	5.53	6.1	4.03	2.83	2.21	30
1995	1.74	1.44	0.41	0.96	1.64	2.46	2.83	3.63	4.44	4.78	6.02	6.83	37.18
1996	1.68	1.28	1.12	1.71	3.73	5.71	5.9	5.86	6.21	7.65	6.25	4.78	51.88
1997	3.29	2.58	2.15	1.72	2.2	2.36	2.03	2.3	2.54	3.92	5.02	6.01	36.12
1998	6.87	6.61	3.99	1.74	3.51	7.1	7.02	5.71	5.98	8.03	5.36	3.58	65.5
1999	4.437	4.027	3.968	3.936	3.819	3.538	3.935	4.118	4.246	4.495	4.189	3.513	48.221
2000	3.079	2.884	1.371	0.007	1.362	2.766	3.163	3.727	3.951	3.73	3.075	2.817	31.932
2001	2.822	2.098	1.889	2.499	3.106	3.603	3.244	3.162	3.341	3.833	4.125	3.664	37.386
2002	3.392	3.041	2.905	3.068	3.377	3.739	3.393	3.16	3.341	3.834	4.125	3.664	41.039
2003	3.392	3.041	2.905	3.068	3.377	2.763	2.947	3.218	3.341	3.834	4.125	3.664	39.675
2004	3.392	3.874	3.474	3.099	3.67	4.503	4.485	4.494	4.242	3.823	2.66	1.863	43.579
2005	1.05	1.089	2.865	2.814	3.182	3.682	3.71	4.108	4.521	4.367	3.684	3.328	38.4
2006	3.296	3.192	2.869	2.096	2.006	1.98	2.273	2.793	3.438	4.236	4.245	3.552	35.976
2007	3.374	3.173	2.973	3.093	2.966	3.349	3.711	4.007	4.617	4.672	4.505	4.27	44.71
2008	3.827	3.095	2.83	2.684	2.973	3.016	3.413	3.66	4.07	4.411	4.756	3.899	42.634
2009	3.285	2.949	2.83	2.684	2.973	3.016	2.609	2.854	2.889	3.014	2.996	3.042	35.141
2010	2.786	1.957	2.114	2.981	3.622	3.22	2.955	3.506	4.29	4.224	3.486	3.143	38.284
2011	3.103	2.885	2.537	2.402	2.606	2.941	3.254	3.436	3.657	4	4.23	4.402	39.453
2012	4.472	3.039	2.587	2.7	3.094	3.602	4.024	4.562	4.141	3.49	3.102	2.876	41.689

Appendix B.2: Monthly Hawassa Lake Level (m)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	2.02	1.77	1.32	1.92	2.06	1.95	1.72	2.74	3.10	3.53	3.28	2.47	27.87
1991	2.88	2.35	2.35	1.72	1.58	2.54	3.02	3.02	2.03	2.84	2.77	2.30	29.41
1992	1.96	1.65	1.27	1.93	1.89	1.81	1.58	2.58	3.08	3.36	3.36	2.32	26.79
1993	2.71	2.21	2.21	1.63	1.47	2.47	2.90	2.90	1.78	2.62	2.58	2.25	27.74
1994	1.98	1.60	1.18	1.83	1.76	1.72	1.48	2.41	3.12	3.27	3.27	2.22	25.84
1995	2.64	2.09	2.09	1.56	1.42	2.34	2.69	2.69	1.59	2.44	2.37	2.21	26.12
1996	2.07	1.56	1.10	1.74	1.67	1.71	1.49	2.38	3.05	3.17	3.17	2.22	25.32
1997	2.63	2.04	2.01	1.52	1.42	2.28	2.54	2.54	1.76	2.37	2.25	2.13	25.49
1998	2.12	1.57	1.37	1.81	1.70	1.72	1.60	2.37	3.06	3.08	2.58	2.26	25.24
1999	2.60	2.12	1.90	1.63	1.62	2.34	2.51	2.51	2.05	2.59	2.22	1.88	25.99
2000	2.10	1.57	1.39	1.93	1.69	1.67	1.91	2.36	3.07	3.00	2.47	2.40	25.55
2001	2.59	2.11	1.80	1.79	1.79	2.45	2.54	2.78	2.39	2.73	2.24	1.84	27.04
2002	2.08	1.58	1.13	1.97	1.78	1.68	2.27	2.46	3.09	2.99	2.40	2.52	25.97
2003	2.55	2.11	1.74	1.89	1.89	2.63	2.60	2.91	2.52	2.87	2.27	1.92	27.90
2004	2.11	1.62	1.25	2.02	2.08	1.73	2.54	2.57	3.21	3.05	2.38	2.65	27.20
2005	2.63	2.18	1.79	1.99	2.05	2.84	2.74	2.82	2.60	2.94	2.33	2.09	28.99
2006	2.11	1.67	1.48	2.09	2.30	1.94	2.82	2.62	3.31	3.05	2.44	2.85	28.68
2007	2.74	2.74	1.87	2.05	2.29	3.12	2.87	2.48	2.87	3.01	2.42	2.42	30.86
2008	2.18	1.70	1.80	2.22	2.37	2.02	3.06	2.75	3.58	3.22	2.61	3.02	30.52
2009	2.73	2.73	1.96	2.15	2.53	3.36	3.05	2.29	3.13	3.11	2.50	2.66	32.19
2010	2.10	1.60	2.01	2.33	2.30	1.94	3.05	3.02	3.80	3.29	2.71	3.09	31.23
2011	2.61	2.61	1.97	2.16	2.65	3.37	3.36	2.22	3.27	3.07	2.41	2.72	32.42
2012	1.92	1.47	2.00	2.23	2.14	1.81	2.90	3.13	3.70	3.17	2.62	3.01	30.09

Appendix C: Simulated and Observed

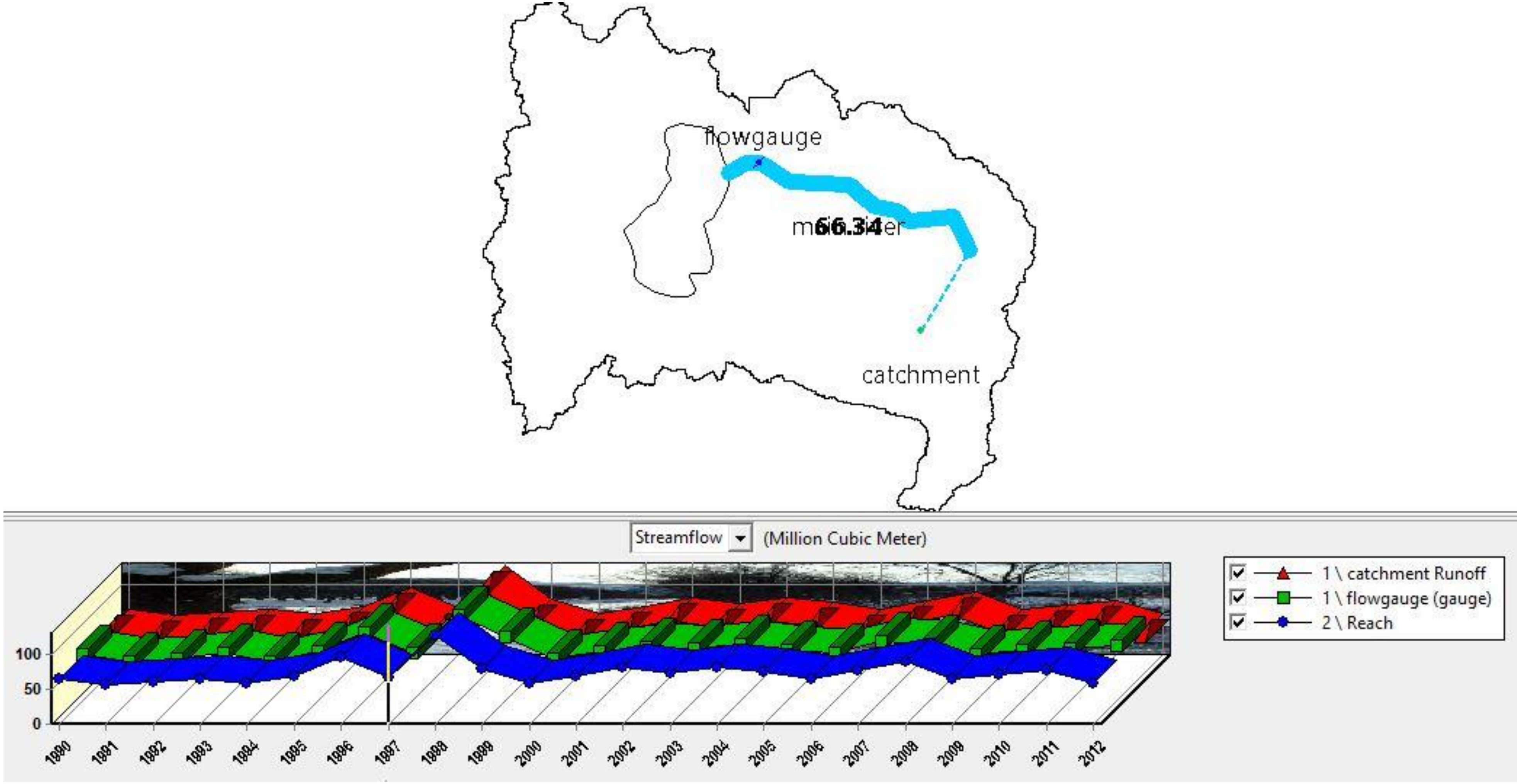

Fig C: 1 Simulated Tikurwuha River flowing into Lake Hawassa

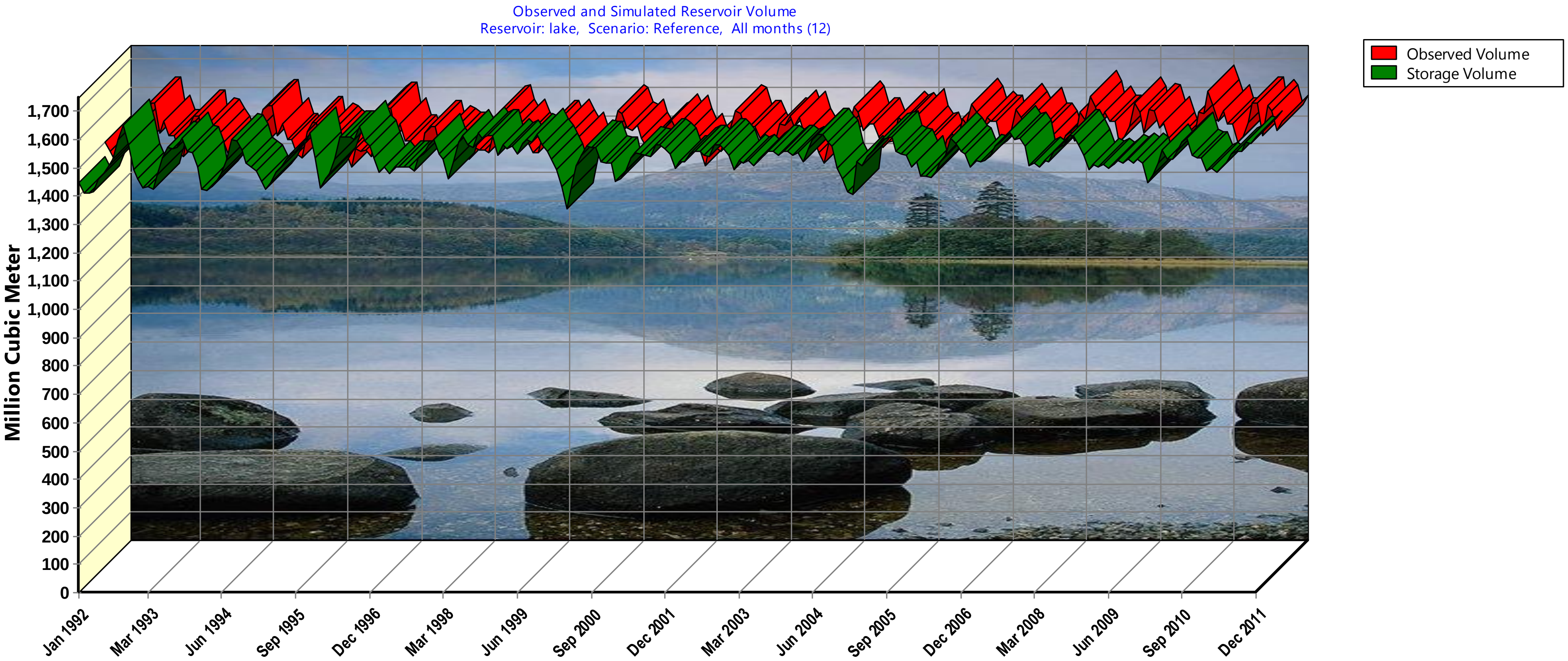

Fig C: 2 Monthly Simulated and observed Lake Volume (1992-2011)

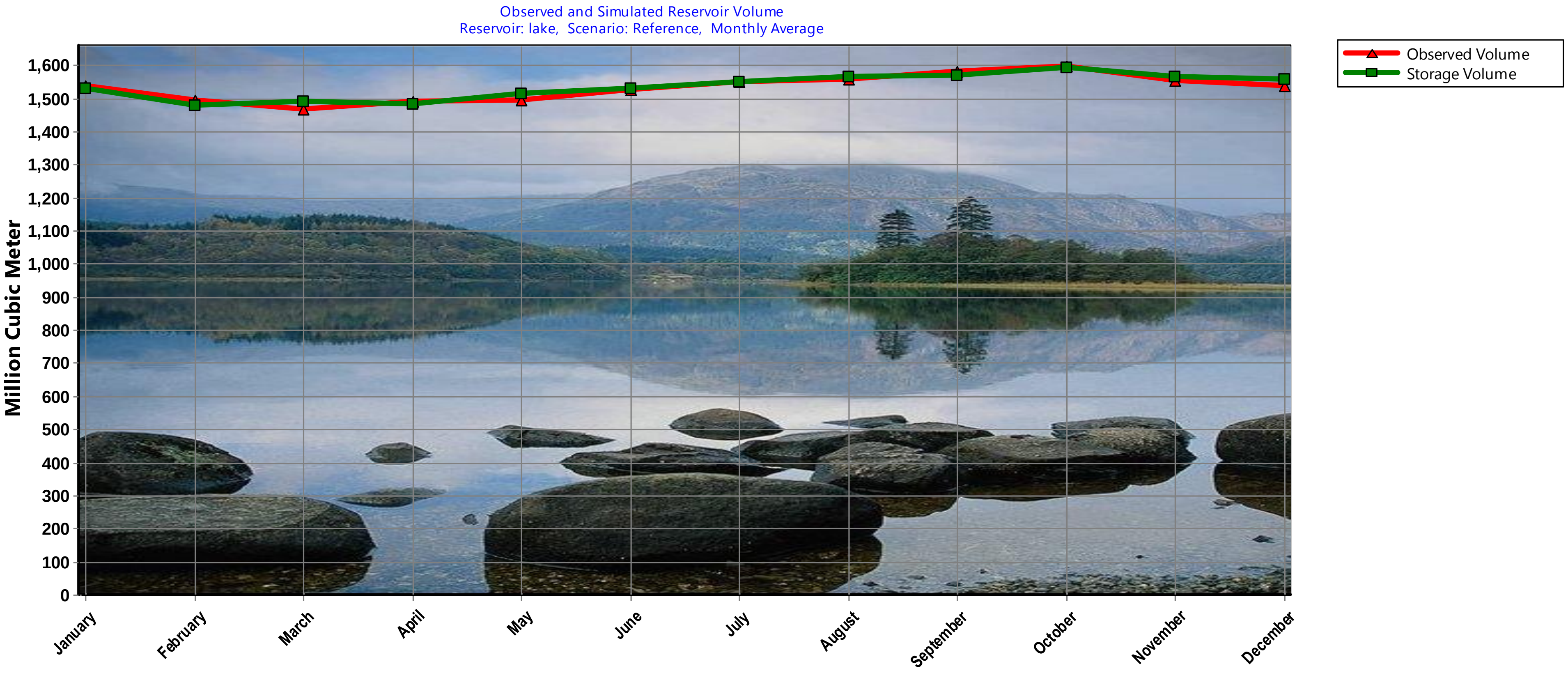

Fig C: 3 Average Monthly Simulated and observed Lake Volume (1992-2011)

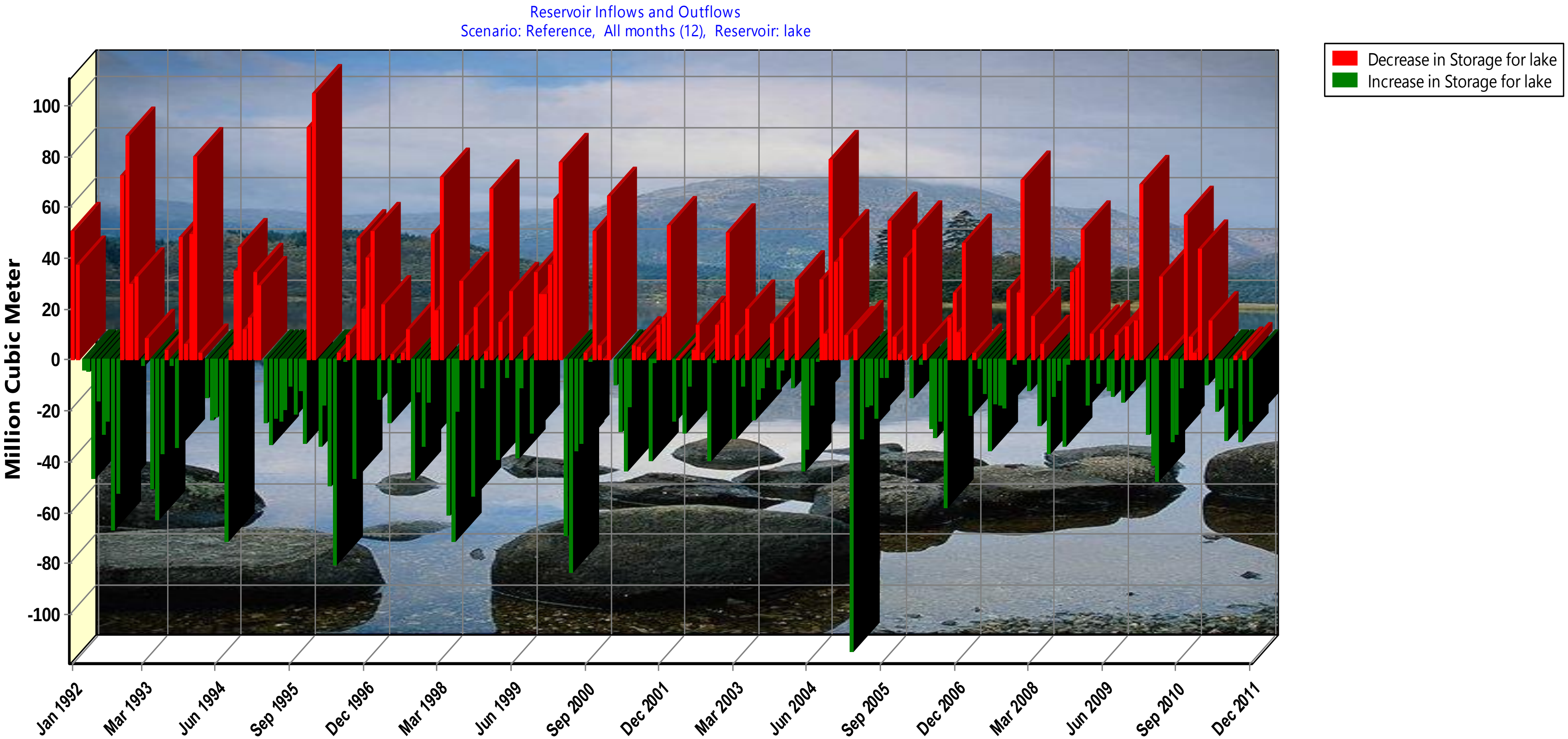

Fig C: 4 Monthly Increases and Decrease in Lake Volume (1992-2011)

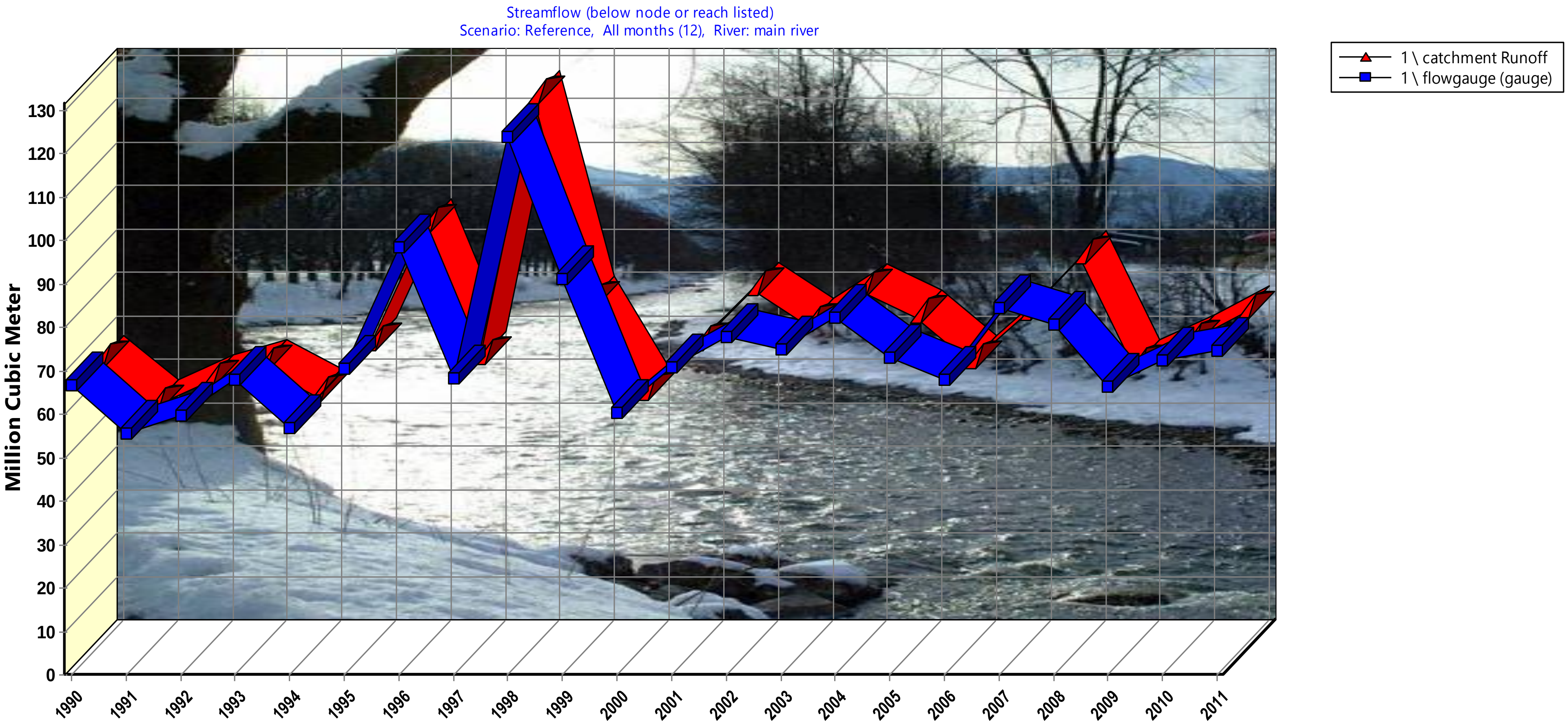

Fig C: 5 Annual Simulated and observed Flow (1990-2011)

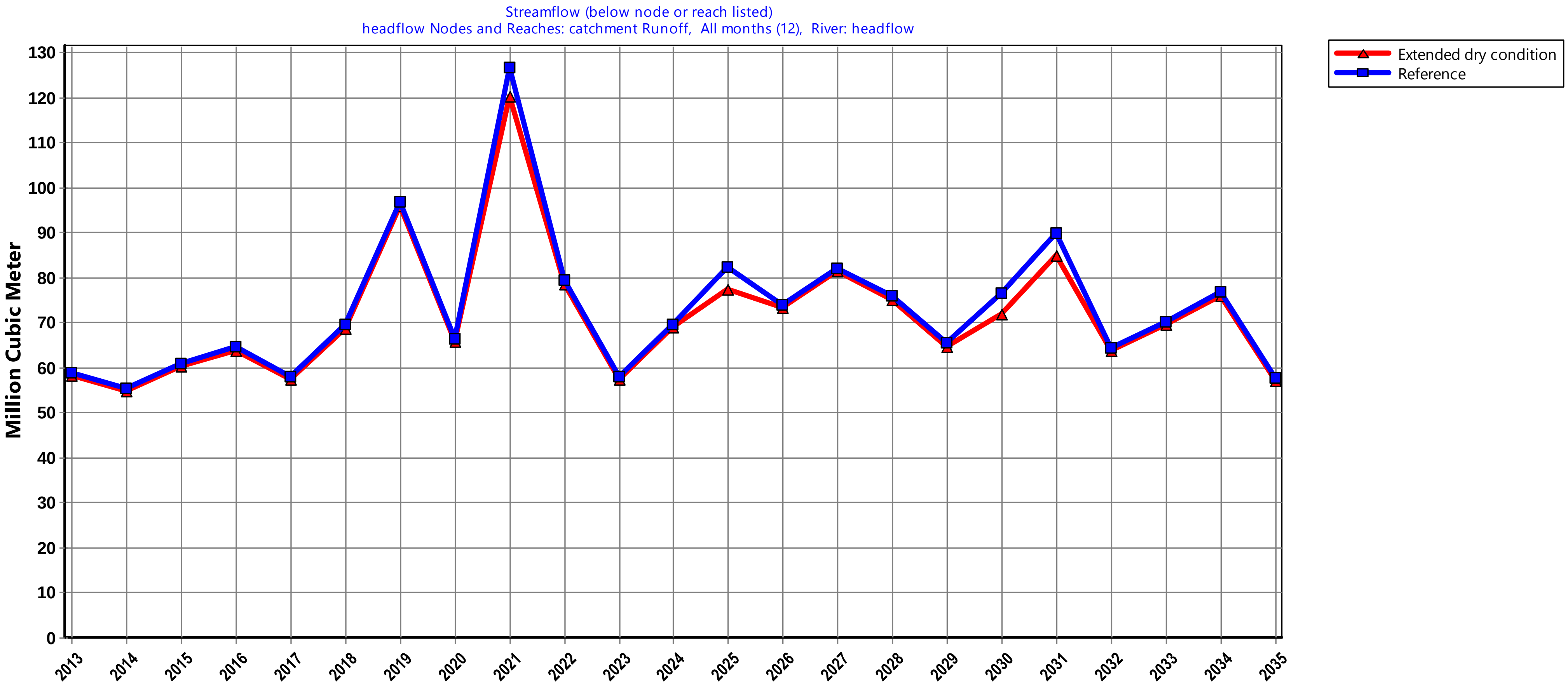

Fig C: 6 Modelled annually stream-flow based on scenario one (2013 to 2035)

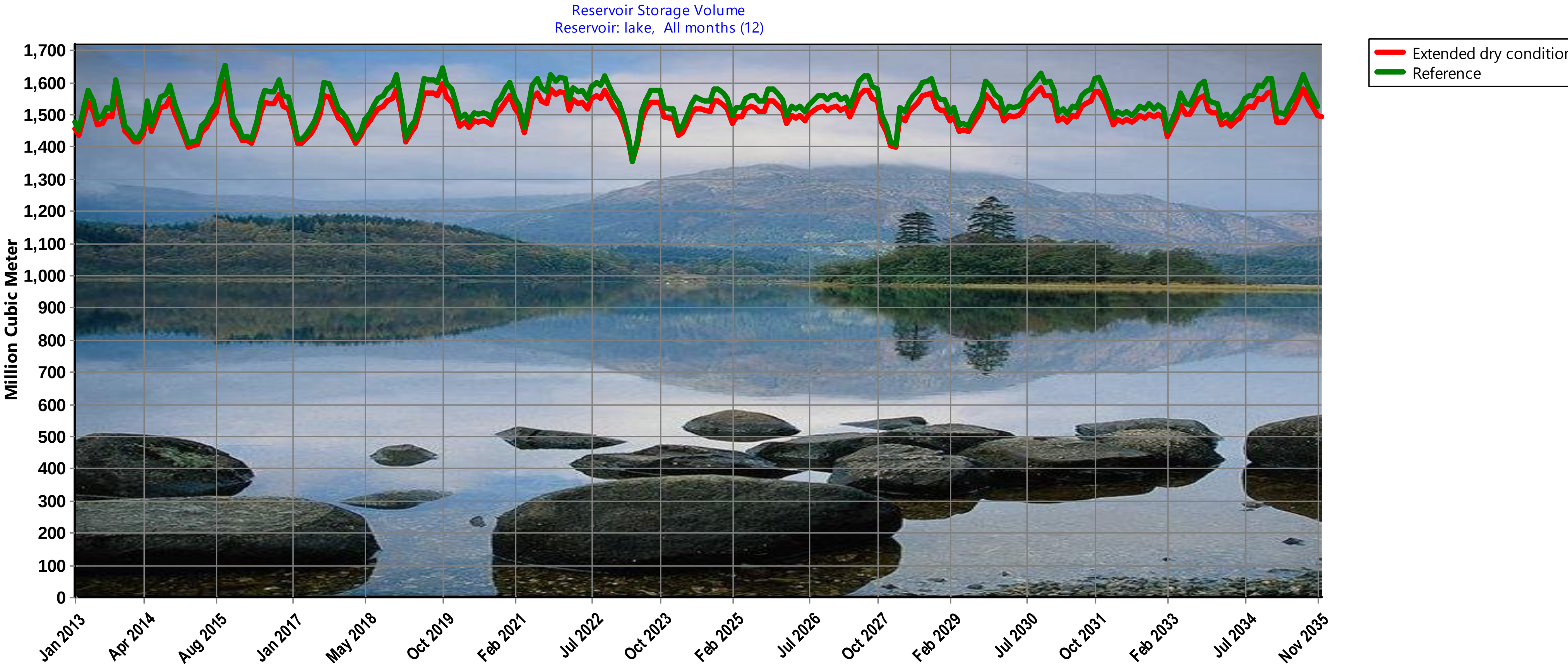

Fig C: 7 Modelled monthly Lake storage based on scenario one (2013 to 2035)

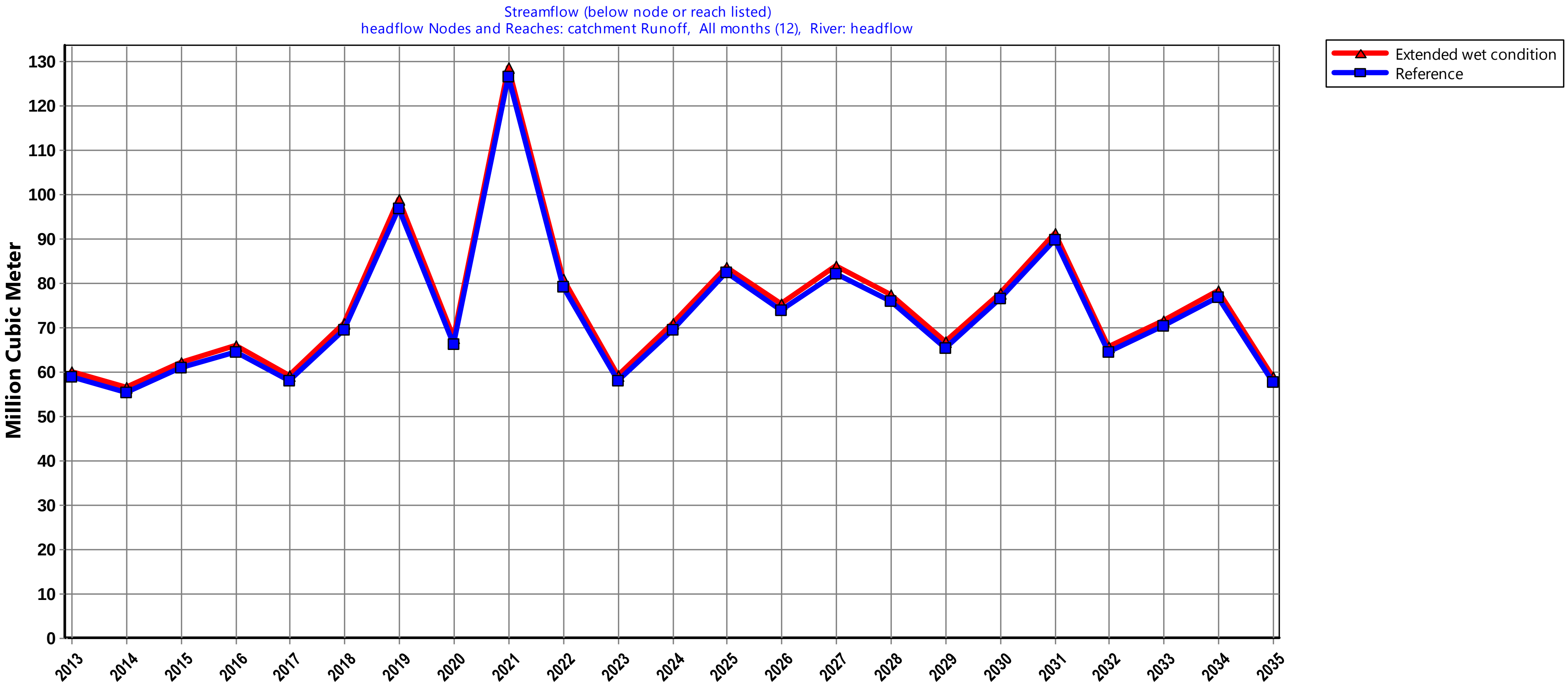

Fig C: 8 Modelled annually stream-flow based on scenario two (2013 to 2035)

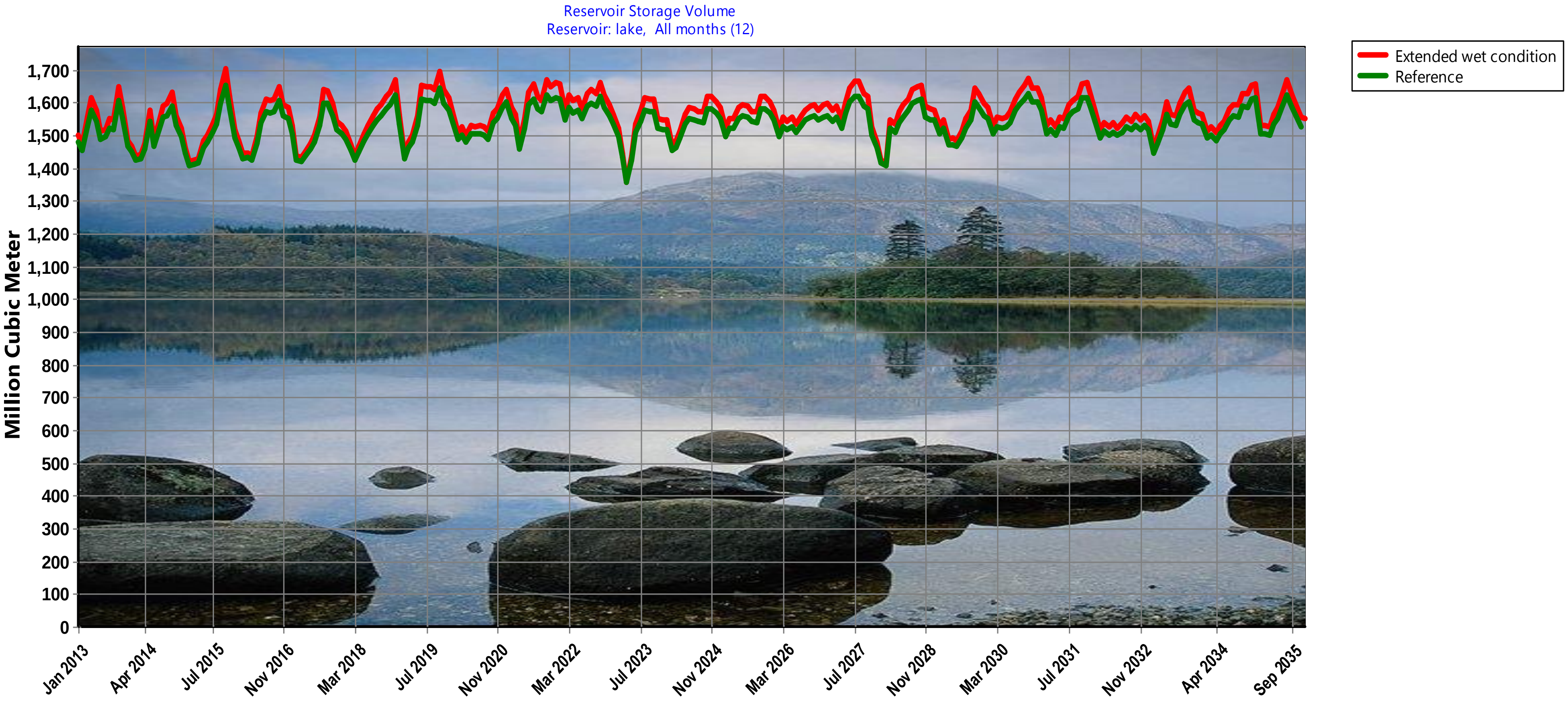

Fig C: 9 Modelled monthly Lake storage based on scenario two (2013 to 2035)

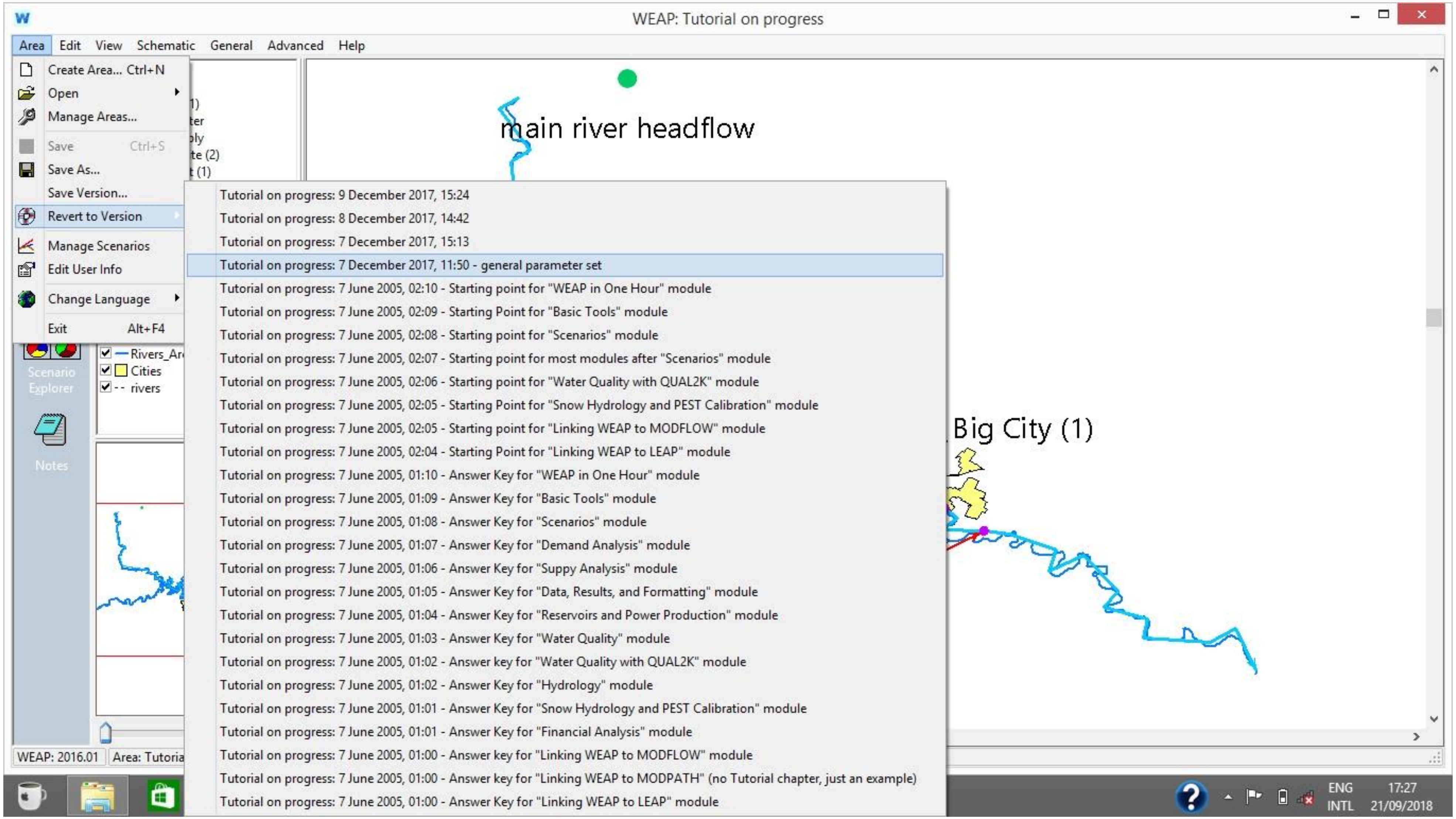

Fig C: 10 WEAP Model various In-built Modules (Source: WEAP Tutorial manual)