Impact of Climate and Land Use/Cover Changes on the hydrology of Lake Hawassa Watershed (Central Ethiopian Rift): Towards Sustainable Water Resources Management

By

Yonas Girma Abebe

A Thesis Submitted to
Ethiopian Institute of Water Resources
Presented in Fulfillment of the Requirement for the
Degree of Doctor of Philosophy

Addis Ababa University
Addis Ababa, Ethiopia
June, 2020

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APPROVAL PAGE

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ABSTRACT

It is generally concurred that climate of the world is changing or at least its variability is increasing and that is bringing significant hydrologic influences on water resources. Consequently, the variation has transformed the way hydrologists view prediction of future hydrologic parameters. The impact to water resources is not only limited to climate variations however. Land use changes have large impacts on these resources as well. Therefore, impact assessment on water resources is a compound effect of natural phenomena and manmade alterations to the environment. Although these modifications have a profound impact on many aspects of the environment, wetlands, especially lakes, are among the most significantly affected.

Lake Hawassa is one of the extensively impacted Ethiopia Rift Valley Lakes. Perhaps the most notable recent changes in the Hawassa watershed were the Lake Hawassa level rise and the flooding of Hawassa town in 1998. Tikur Wuha River discharge increase and the decline thereby disappearance of Lake Cheleleka was attributed to the increasing siltation caused by alarming deforestation of the eastern catchment. The impacts were reported to be of both natural and anthropogenic origin. However, little was done to scientifically address these effects. The investigation entail understanding the hydrologic regime shift caused by the climate variability in the recorded meteorological parameters and anthropogenic factor as in the land use land cover change in the watershed. Therefore, this thesis focuses in testing and detecting the presence of significant trend in hydro-meteorological variables, identifying the amount, distribution and time of land use land cover changes, assess the morphometric change in Lake Hawassa and evaluate the dominant hydrological processes using coupled surface and groundwater modeling framework.

Mass and double mass curves analyses of rainfall in four stations (namely Hawassa, Haisawita, Yirba and Wendo Genet) within and nearby the watershed showed that there is no trend in the rainfall of the area while Tikur Wuha River flow at Tikur Wuha Bridge and Dato village depicted jumps. Trend and homogeneity test of Lake Hawassa level, rainfall, temperature and flow at Tikur Wuha by Mann-Kendall and Pettitt's test revealed that all had a trend (at 5% significant level) and non-homogeneity characteristics except rainfall. Change point analysis illustrated the year 1987-1988 was the year where most of the hydrometeorological parameters showed changes. As a result, Landsat images taken in the years 1973, 1987 2003 and 2019 were selected for image classification and the period from 1973 to 1987 and 1988-2003 were taken as statistically stationary periods for model development (calibration and validation) and study the impacts. The results of hydrometeorological analyses were the bases for land use land cover change analysis and hydrological modeling activities.

Land use and land cover maps were derived from ground truthing and satellite imagery by supervised image classification technique. The analysis identified six major land use land cover forms (Built up, Cultivated, grassland, grassed wetland, shrub and forested land and water body). The change investigation displayed cultivated land was the dominant land use form in Hawassa watershed. Built up area increased by 188% while shrub and forested lands diminished by almost 23% during 1973-2003. Recently, urban areas increased by over 800% proving to be the fastest growing land use type. The land use changes in the only perennial Tikur Wuha River catchment also followed similar patterns with the entire Hawassa watershed.

In this study, a bathymetric map was prepared using advances in global positioning systems, portable sonar sounder technology, geostatistics, remote sensing and geographic information system (GIS) software analysis tools with the aim of detecting morphometric changes against the first extensive hydrographic map of Lake Hawassa in 1999. Results showed that the surface area of Lake Hawassa increased by 7.5% in 1999 and 3.2% in 2011 from that of 1985. Between 1999 and 2011, while water volume decreased by 17%, silt accumulated over more than 50% of the bed surface has caused a 4% loss of the Lake's storage capacity. The sedimentation patterns identified may have been strongly impacted by anthropogenic activities including urbanization and farming practices located on the northern, eastern and western sides of the lake watershed. The investigation also demonstrated geostatistical modeling approach to be a rapid and cost-effective method for bathymetric mapping.

Finally, a coupled surface and groundwater modeling system, MIKE SHE, suitable to model lake watersheds effectively, was used to diagnose the responses of Tikur Wuha catchment in Hawassa watershed to LULC changes and climate variability. Two models based on the Bridge and Dato village stations flow data were developed to tackle the huge difference between the two data sets. The models were calibrated and validated, and were able to capture the dominant runoff processes and streamflow dynamics of the catchment. Streamflow simulations and water balance assessment indicated that, evapotranspiration accounted 85%, while the other components represented 22% of the total rainfall the area received. This showed that the watershed had given off its reserves to satisfy the water balance of the hydrologic components. The models demonstrated that climate variability was found to have impacted unsaturated zone storage but have smaller impact on the rest of the water balance components in the watershed during the study period. Tikur Wuha River flow and the components of the catchment water balance were adversely modified by land use land cover changes; especially evapotranspiration, overland flow, unsaturated zones storage, base flow to river and the saturated drain to river components. These indicated that impacts in the watershed are reversible with the proper catchment management supported by sound land use policies. Annual water balance was moderately affected by the changes while streamflow was most susceptible to land use change for both models of the catchment. Simulated streamflow indicated that the Bridge model deteriorated with time while the Dato model simulated well but failed to distinguish land use impacts. The study highlighted the importance of soil and water conservation interventions in the various LULC classes particularly in the agricultural land use systems. The study showed the gaps in streamflow data accuracy and emphasized on the reassessment of the stations condition.

Key Words: Change Detection, Bathymetry, MIKE SHE, Land Use Land Cover (LULC), Lake Hawassa

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DEM: Digital Elevation Model.. 11

DN: Digital Number 58

ENSO: El Niño–Southern Oscillation.. 25

ERV: Ethiopian Rift Valley 3

ET: Evapotranspiration... 1

ETo: Reference Evapotranspiration... 12

FAO: Food and Agriculture Organization of the United Nations.............................102

GPS: Global Positioning System 76

Ks: Sturated Hydraulic Conductivity..103

LAI: Leaf Area Index 99

LULC: Land Use Land Cover 4

MAE: Mean Absolute Error 105

ME: Mean Error..105

mNDWI: Modified Normalized Difference Water Index.................................. 77

MoWIE: Ministry of Water, Irrigation and Electricity 77

NMA: National Meteorology Agency 11

OL: Over Land...116

CHAPTER 1: INTRODUCTION

1.1 Background

Water resources management is one of the fundamental pillars of development for a nation and a global concern as witnessed in the sustainable development goals of the United Nations. Fresh water resources in particular call for a prudent management because these resources are limited. Generally, it is concurred that climate of the world is changing and it is bringing significant hydrologic influences (Tong et al., 2012). As a result, water resources in dry subtropical regions may be impacted adversely (Cisneros et al., 2014).

Similarly, land use changes have large impacts on these resources (Wagner et al., 2013). Ecosystems are being modified by a multiplicity of interacting natural and anthropogenic factors (Kulakowski et al., 2011). While it is commendable to see that there is no doubt within the scientific community of the need to manage water resources, water resource systems have been misused worldwide (Brönmark & Hansson, 2002). Lake and wetland ecosystems belong to the most abused and most vulnerable resources to human intervention and natural phenomena (Odada et al., 2005). Literatures indicate that about 80% of the lakes and wetlands are either degrading or disappearing globally (Schneider & Hare, 1996; Shodimu, 2016). Catchment modification by humans and climate are determinant factors that influence the global energy and water cycle (El-Khoury et al., 2015) that exacerbate the continued degradation of these resources. Spatial and temporal variation of water balance components such as surface runoff, soil moisture, evapotranspiration (ET), groundwater and streamflow are usually influenced by land use and climate impacts (Deng et al., 2015; Memarian et al., 2014).

While the World Meteorological Organization (WMO) defines climate variability as variations in the mean state and other statistics of the climate on all temporal and spatial scales, climate change is defined by the United Nations Framework Convention on Climate Change (UNFCCC) as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (WMO, 2020). Climate and human influences on the different aspects of the hydrological cycle and their effects on the economic societies have been extensively researched by the international community, both worldwide and locally (Jiang et al., 2015). Global climate models (GCMs) project variations in precipitation across the globe indicating that there will be an increase in rainfall in both the dry and wet seasons in Ethiopia (Garedew et al., 2009; Keller, 2009). Projections of future streamflow study in the great horn of Africa region indicated large decreases for all major rivers in Ethiopia and increases in the equatorial parts of the region at the end of the century (Hirpa et al., 2019). A study conducted in Awash basin, showed that there was no projection of decrease in water availability in the rainy months of July and August, while April-June months showed a decreasing precipitation and increasing temperature leading to lower water availability (Taye et al., 2018). These increases are said to have a direct influence on the hydrology of the region signifying the decisiveness of climate variations.

In the past few decades, land use change impacts were observed in Ethiopia and Ethiopian rift valley in particular. Forest degradation and conversions of woodlands to cultivated land were evident in central rift valley region (Dessie & Kleman, 2007). The question however remains whether these changes in climate and human intervention in terms of land use are traced from the recorded meteorological, hydrological, morphometric and land use land cover parameters to understand, manage and remedy the impacts.

In most water resource management assessments, hydrometeorologic inputs are assumed to be the realizations of a random process (Kundzewicz & Robson, 2000), which can be defined by a probabilistic function implying the future is indistinguishable from the past (Matalas, 1998). Nevertheless, hydrometeorologic characteristics may change over time from either natural or anthropogenic causes which themselves are changing as well. Variations in precipitation amount and pattern and modification of flow regimes of rivers and inland water bodies are considered to be indicators of climate or anthropogenic changes. That is why investigating alterations in streamflow records and identifying signatures of natural or anthropogenic origin has been an area of recent interest (Kundzewicz, 2005).

As stated above, Ethiopia is impacted by climate and human induced changes. One of highly impacted regions is the Ethiopian Rift Valley (ERV) system. The ERV, comprising a chain of more than 15 permanent lakes formed by volcano-tectonic depressions in the rift floor, creating what we now call Rift Valley Lakes housing indigenous biota and fauna populations, is of great influence on national and regional hydrodynamics (Halcrow, 1989). These lakes have ecological, economic, cultural, and scientific importance to the local population and the region at large (Ayenew, 2005; Dadebo et al., 2014; Hirpo, 2016). The research focus of this thesis, Lake Hawassa watershed (Figure 2.1), referred to as Hawassa watershed here after, is located in the central Ethiopian Rift Valley. Therefore, a better understanding of the impact mechanism of climate and Land Use Land Cover (LULC) changes on hydrological processes in such watersheds is crucial for sustainable water resources management (Li *et al.*, 2015).

1.2 Problem Statement

Recently, various development activities are taking place in the Ethiopian Rift Valley basin. Moreover, climatic variations also depict the natural influences. Due to these development endeavors and natural phenomena, the lakes in the region are subjected to some environmental and ecological changes which are visible in the quality and quantity alterations of their water resources. Perhaps the most notable recent changes in the Hawassa watershed were the Hawassa lake level rise and the flooding of Hawassa town in 1998. These alterations were widely attributed to anthropogenic and natural activities (Abiye, 2008; Belete, 2013).

Hawassa watershed has a unique hydrological system that is closed and open at the same time. The surface water system is closed owing to the topography and it has an open groundwater system hence its freshness. Even so, surface water bodies are integral parts of groundwater flow systems and should be considered as such in the investigation of this watershed system. The hydrological investigation so far in the watershed were partial (they considered surface or groundwater alone), descriptive rather than quantitative, and the justifications rendered as to the causes of hydrological variations were speculative rather than supported by scientific evidences (Ayenew & Becht, 2007). Therefore, integrated surface and groundwater modeling was lacking to understand the system and mitigate the water resources and related problems.

This integrated hydrological modeling entail investigation of the climate variability in the recorded meteorological variables and anthropogenic factor as in the LULC, which is also lacking. Hydrometeorological regime shifts and change points need to be detected to quantify the parameters after the change scenario.

Although LULC studies have been conducted in the watershed, they did not considered the change points on the hydrometeorological parameters. As a result it was not possible to employ the results of these investigations in this study. This necessitated a new LULC analysis that took into account the change scenarios.

Moreover, the hydrological changes have resulted in the modification of the physical configuration of the watershed and its elements. The most significant morphometric changes are said to happen in lakes (Adrian *et al.*, 2009; Williamson *et al.*, 2009). Lakes document the amount and distribution of soil erosion as depicted by the lake bottom surface sedimentation. Morphometric changes require periodic monitoring to identify the rate, amount and location of change with in the Lake.

Therefore, studying the trend and change points in hydrometeorological parameters, the corresponding LULC changes, Lake Hawassa bathymetric characteristics, and modeling the various water balance components at catchment scales considering the temporal and spatial dynamics are vital for sustainable management and utilization of water and natural resources of the Hawassa watershed.

1.3 Study Objectives

In the context of the issues outlined above, this research is focused on identifying change points in meteorologic parameters and LULC properties that influenced the hydrology of the Lake watershed studied in a modeling exercise with the objectives to:

i. test and detect the presence of significant change (trend) in hydro-meteorological variables (temperature, evaporation, rainfall, lake level and stream flow) that explain the changes in Hawassa watershed;
ii. detect the amount, distribution and time of LULC changes in Hawassa watershed (since the time of recording of hydrologic history, 1973);
iii. conduct and evaluate morphometric change assessment in Lake Hawassa between 1999 and 2011;
iv. evaluate impact of climate variability and LULC changes on the dominant hydrological processes using coupled surface and groundwater modeling framework (MIKE SHE) and understand the implications on implementation of water resource management practices.

1.4 Significance of the Thesis

The methodologies of the study are arranged in four key categories to address the major objectives of the research. These are statistical time series analysis of hydro-meteorological data for change detection, LULC change detection, Lake Morphometric analysis and hydrological flux partitioning through modeling, taking in to account the LULC changes, to analyze water resource availability under the changing environment and physical properties of the watershed.

This study provides insight into hydrologic responses to climate and land use changes in Hawassa watershed in the recent past. New approach towards hydrologic modeling by insuring the presence and absence of variation in the climate inputs shows advantage over the assumption that the future is indistinguishable from the past. Moreover, cost effective lake morphometric methodology is demonstrated using a combined uses of remote sensing data and geostatistics. Understanding how LULC and climate changes affect hydrology in the catchment would help watershed managers, agricultural producers, policy makers, and the general public makes informed decisions. This is an important step toward development of strategies for sustainable water resources management.

1.5 Conceptual Framework of the Study

The thesis emphases on detection of changes in hydrometeorological, LULC and Lake morphometrical changes to assess the impact of natural and manmade impacts on Hawassa watershed. Accordingly, there are four main themes that constitute the scope of the study. The investigation examines changes in the hydrometeorological data that substantiate the resulting impact; LULC changes based on the hydrometeorological shifts; detection of hydrographic change on Lake Hawassa; and assessing the effects of climate, LULC and physiographic changes on the watershed through hydrologic modeling. The study is intended to give clues for proper management of the watershed. Conceptual framework of the study is indicated in Figure 1.1.

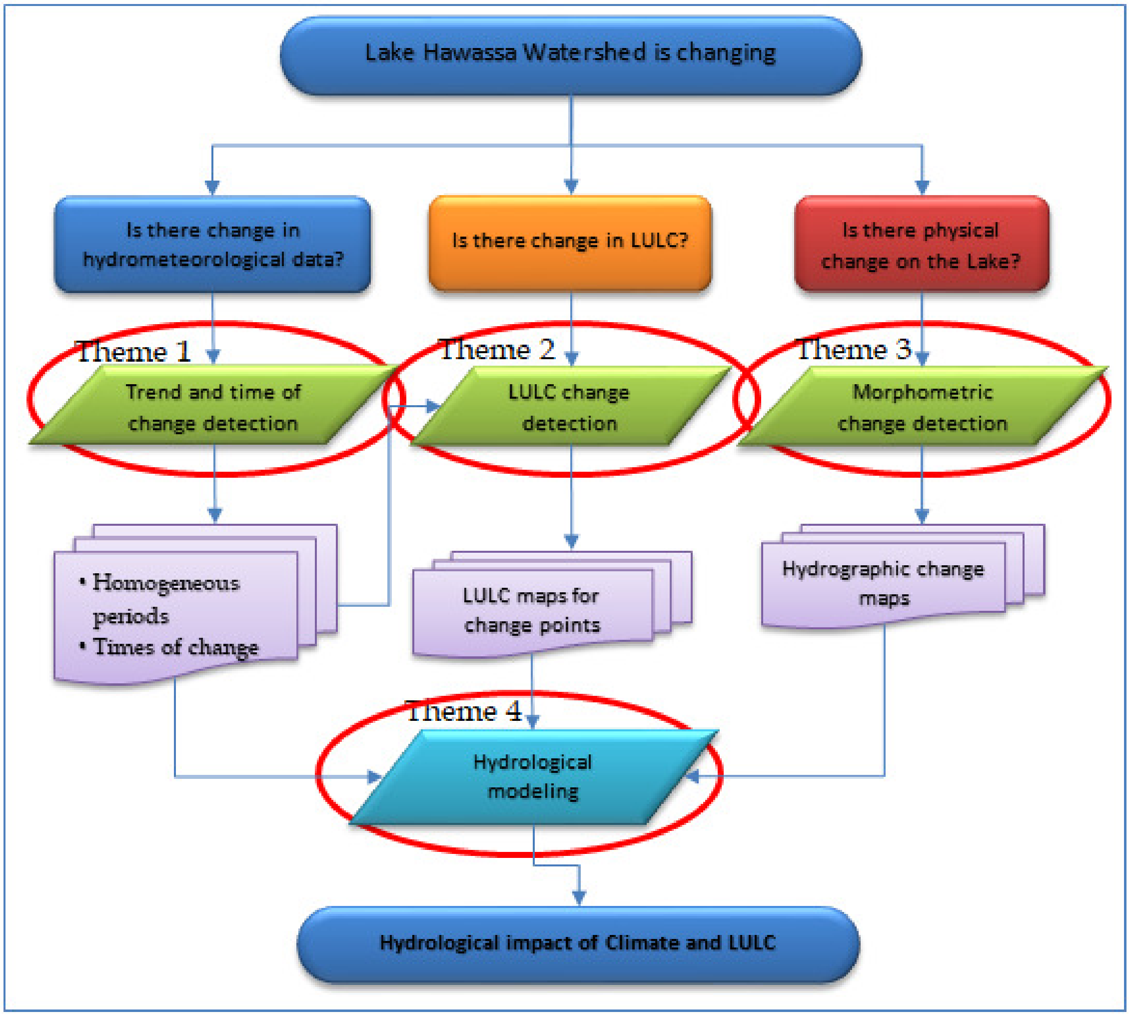


Figure 1.1. Flowchart of the research

1.6 Thesis Organization

This thesis is organized in eight chapters. Each chapter is set in such a way that it is addressing one topic and can standalone. The first chapter introduces the subject matter of the research and provides the problem statement and objective of the dissertation. Chapter two defines and gives watershed characteristics of the study area relevant to the subject of inquiry. Chapter three provides a review of pertinent literature. Chapter four deals with trend and change point analysis of hydro-meteorological variables on which the subsequent chapters are based. Land use land cover change detection and analyses are discussed in Chapter five. Chapter six deliberates morphometric change detection analysis. While hydrologic model development and analysis is covered in Chapter seven, Chapter eight provides the summary of the dissertation.

CHAPTER 2: DESCRIPTION OF THE STUDY AREA

2.1 Study Area

Hawassa watershed is found in the Ethiopian Rift Valley basin. The ERV basin is part of the Afro-Arabian rift system which extends from Jordan in the Middle East to Mozambique in Southern Africa (Girdler, 1991), passing through Eastern Africa dividing the Ethiopian Highlands in to the Northern and Southern scarps. Figure 2.1 depicts Hawassa Watershed situated in the central ERV sub basin.

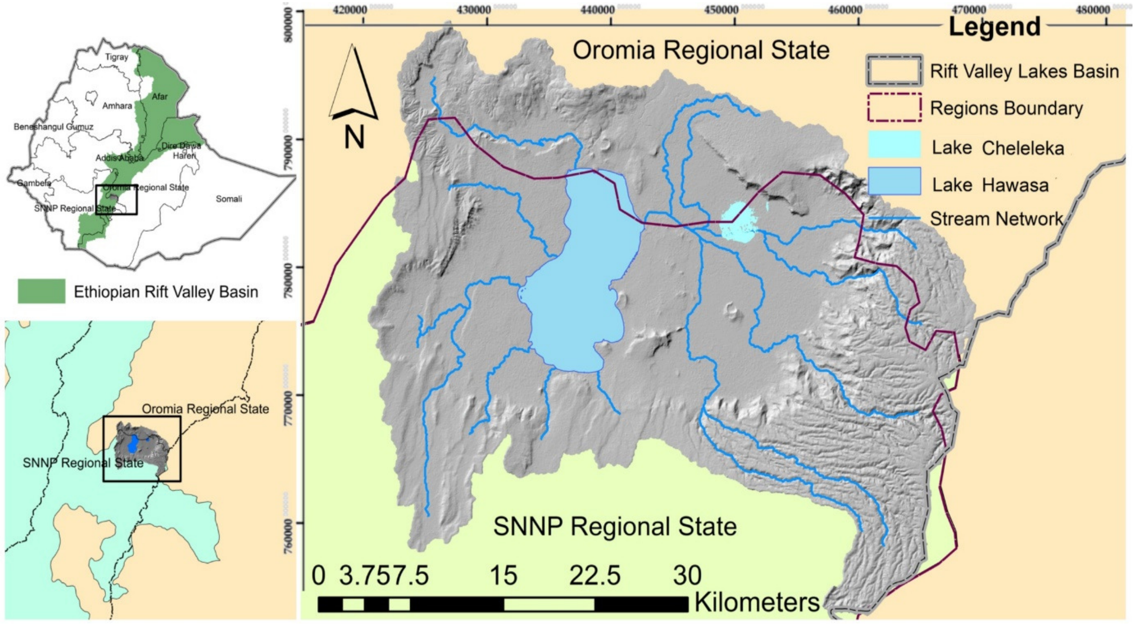


Figure 2.1. Location map of Hawassa Watershed showing the central RVB in Ethiopia

Geographically, the watershed is situated between 6°48'46" – 7°13'55" North latitude and 38°16'44" - 38°43'32" East longitude in the Sidama Regional State (part of former Southern Nations, Nationality and Peoples Regional State (SNNPRS) and Oromia Regional State. The catchment is said to have an area of about 1400 km^2, from which 92 km^2 is covered by Lake Hawassa (WWDSE, 2001). From a 30 m resolution Shuttle

Radar Topography Mission (SRTM) Digital Elevation Model (DEM) analysis, this study found out that the area of the watershed is a little smaller than what was reported earlier. The watershed is bordered by Ziway-Shalla basins (in the north), Abaya-Chamo basin (in the south), Wabi-Shebelle-Genale basin (in the east), and Omo-Gibe basin (in the west). The traditional agroecology classification place the eastern part of the watershed as moist Woina Dega (mid highland) while the western part is dry Woina Dega (Degife *et al.*, 2019).

While the eastern and south-eastern escarpments are relatively well covered by a mixed vegetation, where agroforestry is widely practiced, the western part of the watershed is poorly vegetated (Lemma, 2005). Dense bush covers the north-western parts, which are part of the Senkele wildlife sanctuary. Northern, central and southern parts of the watershed are manly agricultural lands populated by smallholder and mechanized commercial farms.

2.2 Climate of the Watershed

The climate of Hawassa basin is sub-humid and seasonal (Abiye, 2008). According to the data (1972-2008) from National Meteorology Agency (NMA), Hawassa area receives about 980 mm rainfall of which 72.31% falls within the months of April to September. About 40% of the total rainfall in the area and over 50% of wet season precipitation falls during the main rainy season (July and September). The basin is affected by the north-south movement of Inter Tropical Convergence Zone (Belete *et al.*, 2017).

Temperatures fluctuate between -2.8 °C and 34 °C. The daily sunshine hours vary between 7.5 hours in August and 11.7 hours in May, November and December. Monthly average relative humidity values range between 37% and 78%. The average monthly wind speed, at 2 m height, range between 0.43 and 1.4 m/s directed dominantly from northeast to southwest. However, Abiye (2004) reported that west to east blow is common during summer and south to north is observed in May. The reference evapotranspiration (ETo) at Hawassa is 1529.52 mm/year. The minimum ETo is 108.2 mm in the month of July and the maximum is 148.7 mm in the month of March.

2.3 Description of the Study Lakes in the Watershed

Lake Hawassa and the adjoining small Lake Cheleleka are among the several volcano-tectonic lakes formed in collapsed calderas in ERV (Awulachew et al., 2007). These lakes are believed to have been a single lake in the past (Makin et al., 1975). Lake Hawassa is located between 6°59′3.91″–7°7′42.24″N latitude and 38°23′17.8″–38°28′52.9″E longitude while Lake Cheleleka was found about 6 km east of Lake Hawassa. These lakes are the source for commercial fishing, home for many flora and fauna, and a recreational site. Moreover, the local community derives domestic, livestock and irrigation water mainly from Lake Hawassa and Lake Cheleleka before its extinction. According to WWDSE (2001) the Lake Hawassa has an average depth of 13.6 m, maximum depth of 23.2 m and seasonal level fluctuations of 0.66 m. In recent years, Lake Cheleleka has disappeared into the wide swamp south of the Lake signifying importance of the environmental changes taking place in the watershed.

2.4 Topography and Drainage

The topography of Hawassa watershed is a direct reflection of the volcanic eruption and intensive tectonic activities in the geological time and modification through erosion processes (Abiye, 2008). The area rests in a collapsed caldera forming an endorheic basin where here is no river that neither comes in nor leave the catchment. The least elevated point is Lake Hawassa, at 1680 m above sea level, while the highest point peaks to 2995 meter above sea level at the caldera edges towards the south-east (Figure 2). The low laying Lake Hawassa receives surface water from the several seasonal streams and the only perennial Tikur Wuha River.

Although Lake Cheleleka has disappeared currently, its swamp cumulate water from streams (Gomesho, Wedesa, Wetera, Werka and Wesha) draining the northern and eastern escarps. The western, northwestern and south western parts of the watershed are characterized by undefined stream lines that drain into small sub basins which limited stream development. In recent times with the severity of soil erosion and formation of gullies stream networks are generated in the north western part. A relatively small area located at the south western part of the watershed is drained by small seasonal streams like Shasho, Lewa, and Tenkerame emptying themselves into Lake Hawassa (Hawassa University, 2014). These streams apparently originate from hills such as Werencha, Werema, and Tedelcha; and drain Doyo Otilcho, Jara Dado, Jara Hinesa and Jara Kerara kebeles. Even if the study watershed is a closed basin, some studies have made known that there is groundwater inflow and outflow to the surrounding watersheds (Ayenew, 2009; Gebreegziabher, 2005; Tilahun, 2006). Recent development activities have altered the natural drain system of the watershed. The major alteration observed was the asphalt road connecting Hawassa and Shashemene towns between Tikur Wuha and Toga villages. Surface runoff in the former Shallo farm was hydraulically isolated from flowing into the sub basin replenishing Lake Cheleleka which forced recent studies to have used the road as a waterdivide, which the author finds inordinate due to the presence of culverts. The land configuration and drain network of the watershed are shown in Figure 2.2.

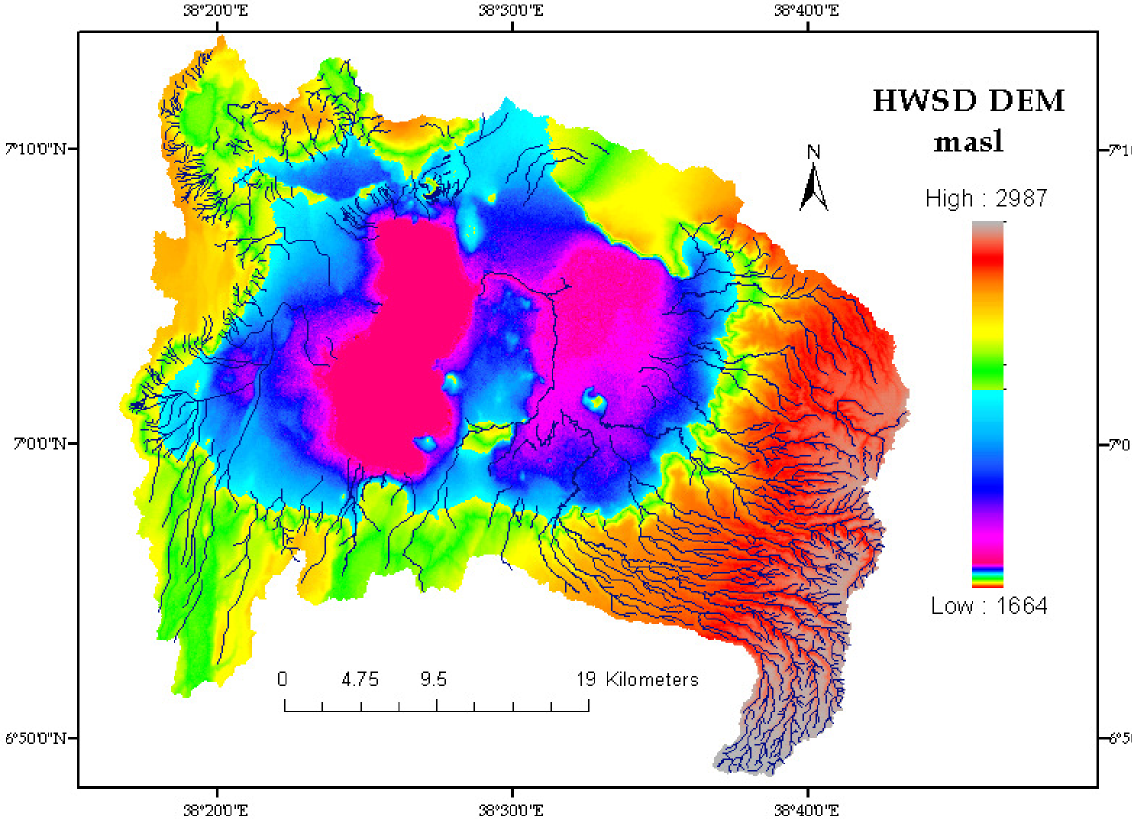


Figure 2.2. Topography and drain network of Hawassa watershed

Figure 2.3. Elevation profile of some Ethiopian Rift Valley Lakes

Topographically, Lake Hawassa is found at the highest point compared to the other rift valley lakes in East Africa. Its elevation and geologic formation favor seepage through faults, cracks and sediments that force water to flow to the low laying lake aquifers. Figure 2.3 shows the relative elevation of rift valley lakes across a line joining the lakes Koka, Zeway, Langano, Abajata, Shalla, Hawassa, Abaya, Chamo, Chew Bahir and Lake Turkana.

2.5 Soils of the Watershed

Soil investigations in the watershed were made by different organizations for diverse purposes. As a result, many classification and sub grouping of soils of the watershed exist in literature. One of the detailed soil classification studies in the watershed was conducted in 1987 by the basic seed farm project (WWDSE, 2001). Water works design and supervision enterprise (WWDSE) has also studied the soils of the watershed for the purpose of agricultural development. The rift valley basin master plan study has carried out investigation on the soils of the basin where specifically soils of Lake Hawassa catchment were also separately studied and mapped (MoWR, 2010).

More recently, Hawassa watershed development plan for sustainable natural resources management project of Hawassa University and SOS Sahel Ethiopia likewise studied the major soil types (Hawassa University, 2014). In these studies and others, the major soil types of the watershed were identified as Andosols, Cambisols, Leptosols and Luvisols (see Figure 2.4).

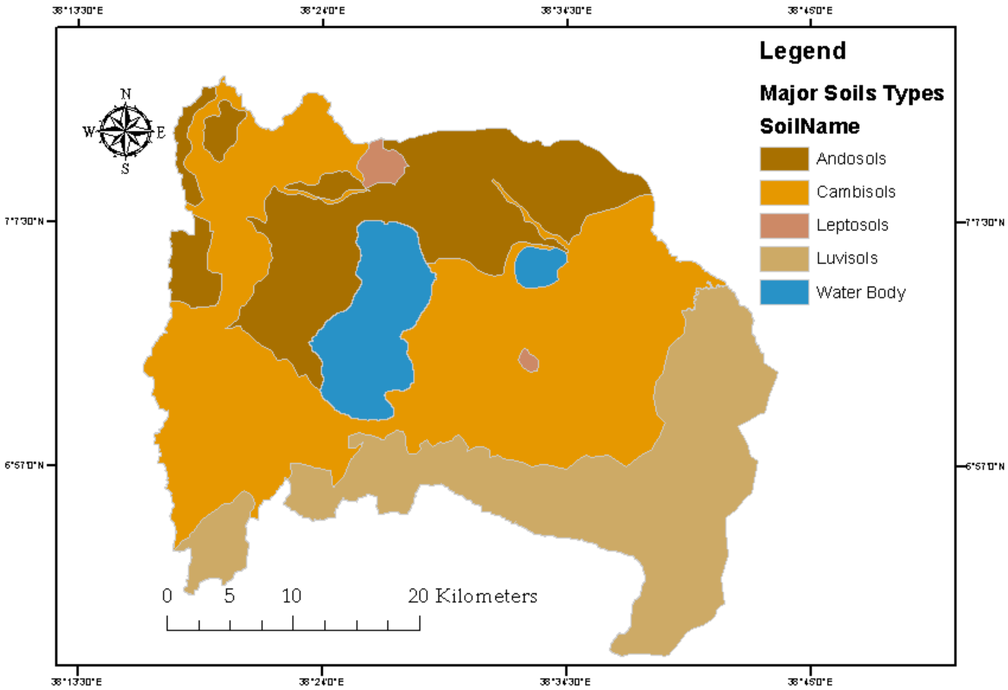


Figure 2.4. Major soil types in Hawassa watershed modified from WWDSE, 1999

According to the above mentioned studies, Andosols in the watershed are deep, well drained and fertile soils with pH value of 6.7- 7.3. This soil type covers 21.1% of the total area, highly productive and found in mostly up land agricultural fields and forest area. Cambisols are the dominant soil type, covering about 45% of the watershed area. This soil type is very deep, well-drained and having neutral to slightly alkaline pH. It is found on gentle sloping to level plains where it is intensively cultivated with annual and perennial crops. Luvisol is dominant on level plain in the eastern part of the watershed that account for 25% of the total watershed area. This soil type is very deep, well drained, has neutral to strongly alkaline pH depth wise from top to bottom. It covers intensively cultivated fields with annual and perennial crops. Leptosols cover only about 1% of the watershed. These soil types are described in Table 2-1.

Table 2-1. Major Soil types of Hawassa watershed described (Modified from MoWR, 2010)

Soil Name	Soil type description
Andosol	Well to excessively drained; moderately deep to very deep(pumice below 45cm); dark grayish brown to dark yellowish brown; medium and coarse textured; sub angular blocky and massive structured; developed on rolling plain (0-15% slope)
Cambisol	Well to excessively drained; moderately deep to very deep(gravely and pumice below 60cm); dark reddish brown, grayish brown and very dark gray; fine to coarse textured; weak to moderate fine and medium sub angular blocky structured; non calcareous Cambisols developed on a level to very steep topography (0-15%)
Leptosol	Excessively to well drained; very shallow; dark brown to very dark yellowish brown; medium textured; weak to moderate medium sub angular blocky structured; friable moist; slightly sticky and slightly plastic wet; slightly to non-calcareous Leptosols developed on a hill with slope >8%
Luvisol	Well drained; deep to very deep; dark brown to dark reddish brown; fine and medium textured; moderate, fine to coarse sub angular blocky

structured; non-calcareous Luvisols developed on medium to high gradient mountains with slope of 5-30%.

2.6 Land Use Land Cover (LULC) in Hawassa Watershed

Lake Hawassa Sub-basin Integrated Watershed Management feasibility study (first phase) of the then Ministry of Water Resources identified 12 major land cover types (MoWR, 2008). Later in the third phase of the same study (MoWR, 2010) the land cover classification was raised to 19 (see Figure 2.5). These studies and other several studies (Abraha, 2007; Degen, 2016; Eshete, 2009; Hawassa University, 2014) indicated that the watershed is dominated by cultivated land use type. Private fragmented farms are found distributed all over the catchment while large state owned farms are mainly located in the north and western parts of the catchment.

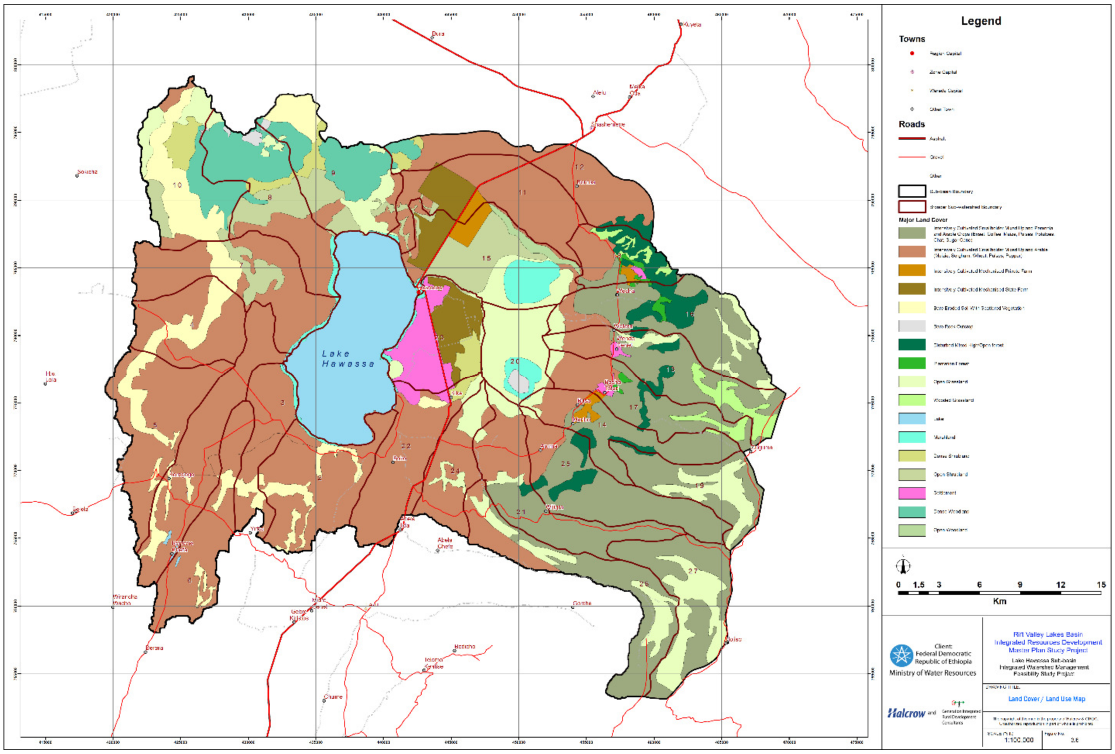


Figure 2.5. Land cover map of Hawassa watershed (MoWR, 2010)

Shrub land and forest lands, both natural and plantation forests, are found primarily on the high lands of Wondo Kosha and Wondo Genet areas. Mixed agroforestry is practiced around Wondo Genet and its use is expanding in the recent days. Open grass lands are mainly distributed around the Cheleleka wet lands and Senkele wildlife sanctuary. Lake Hawassa forms an important land cover type that gave the watershed the name. Hawassa town and small villages such as Wondo Genet, Tikur Wuha, Alamura, Kike and many others formed the smallest but ever growing LULC in the watershed which is settlement area.

2.7 Geology and Tectonic Activities

The study area, located on the central segment of the rift system known as the Nazret-Hawassa segment, exhibits the same nature and history of development with the ERV system. The Ethiopian rift system is the result of Cenozoic volcano-tectonic and sedimentation processes extending from Lake Abe, Afar-triple junction and dies out southward in to Lake Turkana and Lake Stifane rifts south of Lake Chamo (Tilahun, 2006). Abiye (2008) compiled the litho-stratigraphy of Hawassa watershed into four broad categories.

Alkaline and peralkaline rocks comprise basalt and ignimbrites of the plateau trap series and pyroclastic and rhyolitic rocks. Basaltic and ignimbrites of the plateau are the most ancient rocks exposed in the base of the eastern caldera wall. The rift pyroclastics and old rhyolite lava flows are exposed on the eastern and western sides of the caldera wall. *Basaltic lava flows*, basaltic hyaloclastites and scoria cones are found in the southeastern side of Lake Hawassa forming mounts Tabor and Alamura. *Acidic volcanic rocks* pumice flows, pumice falls and ashes, and rhyolites are dominantly distributed around the Corbetti caldera north of Lake Hawassa. These consist of pyroclastics (forming the eastern and western caldera wall), pumice falls and ashes and rhyolites with associated obsidian flows. *Volcanoclastic lacustrine sediments* cover mainly the floor of the caldera and are the only non-volcanic formations in the area. These sediments are dominantly distributed with large stretches at the eastern and western sides of the lake and overly the ignimbrites.

The geologic structures of the study area depict three types of faults based on their strike directions. The NNE-SSW, N-S running, NW-SE and E-W running faults/fracture zones, dissect the caldera floor acting as groundwater transfer lines to/from the neighboring basin. Evidenced by high seismicity and geothermal activities, the Hawassa caldera is situated in a place where younger and active volcanism and recent tectonic activities took place (Tilahun, 2006). Since 1996, ground cracks have developed around Muleti village and Derba area the area to the west of Lake Hawassa. While the cracks on Muleti had average width of 2.5 m, with a depth of 8-12 m and maximum length of 2.4km, the cracks on Derba area have a width of 2-8 m and observable depth up to 5 m with no vertical displacement. A tectonic mechanism that could fairly explain the occurrence of fissures in Muleti and such places in the caldera system is an upward propagating aseismic elastic strain (Ayalew *et al.*, 2004; Tilahun, 2006).

CHAPTER 3: LITERATURE REVIEW

3.1 Introduction

The aim of this chapter is to assess wealth of literature available on the study watershed regarding the four focuses of this dissertation. The chapter deals with reviewing previous endeavors to understand meteorological data analysis, land use land cover change studies and its impact on the watershed and morphometry of the Lake, and the general impact on the hydrology of the watershed. The section follows the general approach of the dissertation in that, it begins by addressing the two main drivers of change, natural and anthropogenic factors (hydrometeorological variables and land use), and discusses their impacts through physical investigation via hydrological modeling of the Lake watershed system. Water resources management practices are commonly aided by hydrologic models which are fitted to hydrometeorological variables such as river flow, precipitation and temperature. These models take the assumption that stochastic time series remain stationary; believing tomorrow will statistically behave like yesterday. However, some hydrometeorological time series can exhibit abrupt changes possibly caused by local factors (e.g. land-use effect on water yield) or induced by a climatic change (Perreault *et al.*, 2000a, 2000b). This leads to the questioning of the stationarity hypothesis in hydrometeorological time series analysis.

The methodology in this research is to detect changes in the hydrometeorological data, identify the time of change and see the corresponding local changes to attribute these changes to the local and/or climate variability. By identifying none stationarities in the series and partitioning them into stationary segments, water resources management models will be built to reflect the realities.

3.2 Hawassa Watershed Hydrometeorology

The five meteorological station of NMA at Hawassa, Wend Genet, Shashemene, Yirba and Haisawita were sources of long term meteorologic data. Shashemene station is found nearby while the rest are found within the watershed. Among these, the Hawassa station is the only synoptic station. Two flow measuring stations and one lake level recording station exist on Tikur Wuha River and Lake Hawassa respectively.

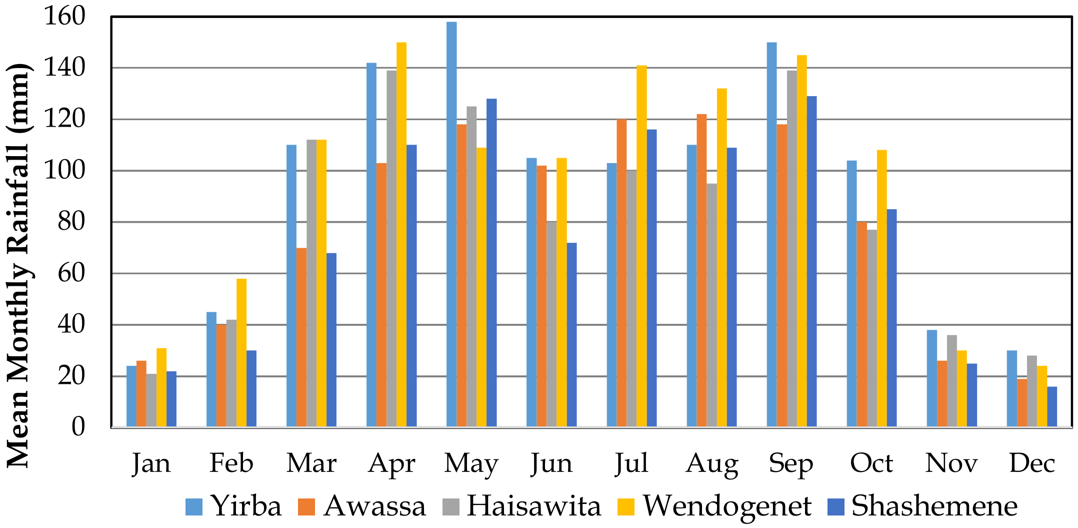


Figure 3.1. Mean monthly precipitation at five meteorological stations modified from Tilahun (2006)

The rainfall pattern in the watershed is bimodal with two peaks in May and September. While the area gets high amount of rainfall in July, August and September, the longest rainy season stretches from March to October with a mean monthly average precipitation of 50-150 mm. The remaining months receive less than 25 mm per month (Tilahun, 2006) as depicted in Figure 3.1.

The mean flow of Tikur Wuha River was reported to have been increased by about 50% in the 1990s than the 1980s (WWDSE, 2001). The decline and disappearance of Lake Cheleleka which fed Tikur Wuha River was explained in terms of the increasing siltation caused by alarming deforestation of the catchment (Gebreegziabher, 2005). The increased water level and groundwater outflow to streams from eastern water bodies and swamps could have cause the increasing water level of Lake Hawassa. Water balance assessment on Lake Hawassa using spreadsheet hydrological model concluded that lake level fluctuations were attributed to land use changes resulting in high surface runoff and siltation (Ayenew & Gebreegziabher, 2006).

Detection of trends in long time series data is of paramount scientific and practical significance because water resources systems have been designed and operated based on the assumption of stationary hydrology (Kundzewicz & Robson, 2000). When this assumption is violated, systems such as hydrologic models which are used to study impacts of climate and human activities do not serve their purpose adequately. The main focus of researches reported in the literature has been towards testing the model performance in split-sample testing without explicitly considering the difference in climatic conditions between the calibration and testing period (Chen & Rao, 2002). In many hydrologic studies, data from hydrometeorological stations are most commonly used with standard quality checks regardless of their purposes. However, nonstationary time series are often encountered in practice. In such cases, stationary stochastic models cannot be directly applied without modifying stationary stochastic models or making changes to nonstationary time series (Kundzewicz & Robson, 2000).

Hydrometeorological trend investigations are meager in Ethiopia. Temperature, rainfall and streamflow in the Gidabo catchment of the ERV basin exhibited trends (Belihu *et al.*, 2018). Time series of the same parameters were tested for trend in the Abay/Upper Blue Nile basin. While trends are registered in temperature and stream flow, rainfall did not show trends in the different stations tested in Abay basin (Tekleab *et al.*, 2013).

There have been few hydrologic modeling investigations on the study watershed (Gebreegziabher, 2005; Shewangizaw, 2010; Tilahun, 2006). Conversely, none of them considered the non-stationarity of hydrometeorological data. In an effort to investigate the effect of natural (ENSO) and anthropogenic factors on the temporal variability of Lake Hawassa water level, lake level and stream flow in the watershed were tested for trend (Belete, 2013; Belete *et al.*, 2017). In this work, statistically significant trends were found in Lake Hawassa level and Tikur Wuha river flow. Lake level experienced a significant upward trend for monthly maximum, average and minimum values. Streamflow also showed an increasing trend for the annual average and for the three local seasons of Kiremt (June-Sep), Baga (Oct-Feb) and Belg (March-May). These results suggest the need to thoroughly detect trends and identify time of changes in the hydrometeorologic time series for hydrologic model development, calibration and validation in Hawassa watershed. Model input LULC of the watershed should also consider these trends.

3.3 Land Use Land Cover Studies

Quite a few LULC investigations were done in the Central Rift Valley region. In this region, cropland area doubled at the expense of woodland and wooded-grassland between the years 1973 and 2006 (Garedew *et al.*, 2009). Trends of land use changes in the region also showed conversion to croplands and bare lands from natural forests, woodlands and grasslands (Li *et al.*, 2018). Cultivated land increased by 13.6% while natural vegetation such as forests and grass land decreased by 9% and 2.6% respectively between the years 1965 to 1998 (Halcrow, 2010).

Studies conducted in the Hawassa watershed also indicated substantial changes in LULCs. Generally speaking, the LULC of the watershed is dominated by cultivated land. In its effort to investigate the 1999 Hawassa town flooding and the lake level rise, WWDSE conducted a land use change detection analysis. It was reported that in 1965 aggregated LULC of the area was 0.4% settlement, 34.3% cultivated, 8.5% water body and 56.8% natural vegetation including grassland, shrubs and forest. This cover was changed to 0.9%, 54.9%, 6.8% and 37.4% for settlement, cultivated, water body and natural vegetation respectively in 1998 (WWDSE, 2001). The report noted that considerable portion of dense woodland had been converted to cultivated land and vicinity of the water bodies was denuded.

According to basin plan study of Hawassa watershed (MoWR, 2010), the land use is dominated by cultivation which occupied 62% in area. While plantation forests in the

Wendo Koshe hills and around Wondo Genet comprised 4%, dense and open shrubland in the Wendo Koshe hills and west of Cheleleka covered 5% of the land. Grassland in association with open grassland in the Wendo Koshe hills, marshland at Cheleleka, smallholder cultivation in the eastern hills and wooded grassland in the eastern hills account for 22% of the total area. Furthermore, marshland covered 1.8% in Cheleleka and around Lake Hawassa, shrubs (3%), bare land 6%, urban areas just under 2% and Lake Hawassa itself occupied just over 6% of the sub-basin.

Abraha (2007) reported that increase of settlement area, conversion of shrubby woodland and bush land in to cultivated land and transformation of Lake Cheleleka in to a swamp were the major changes in the catchment. This study indicated that bush land and shrubby woodland decreased by 167 km^2 and 108 km^2 areas between the years 1973-1986 and 1986-2000 respectively. During the same period, cultivated land increased by 143 km^2 and 100 km^2. Similarly 6 km^2 built up area of 1973 has grown to 8 km^2 and 13 km ^{2} in 1986 and 2000 respectively.

From land use classification analysis of land sat images (1986, 1999 and 2011), Kebede et al. (2014) reported that since 1986 there was an increase in woodland coverage in the eastern highlands of the watershed although forest cover was on the decrease. This was attributed to the growth of agroforestry practice in the locality, mostly chat (*Catha edulis*), Enset and sugarcane. However, the general trends of other land use forms followed the same trend as in the previous studies. In another study, cultivated land was shown to have been increased by 62.7, 77 and 187.9 percent between the years 1972-1992 and 1992-2017 respectively (Degife *et al.*, 2019). This study also indicated that there was a decrease in forest cover by 16.4, 51.9 and 59.8 percent during the same period. Abraha (2007) reported that cultivated and grassland have increase land coverage by 75 and 34.3 percent during the years 1973 to 2000. Based on the above studies, land occupied by crops was 43.6%, 48.7%, 53.4%, and 56.4% in 1973, 1985, 1995, and 2011, respectively indicating it has increased steadily towards the recent times. This suggests that agriculture had and will continue to have higher impact on the hydrology of the watershed.

Gebregziabher (2005) showed the combined effect of climatic and land use changes most likely resulted in an increase of the catchment runoff and lake level. Moreover, it was reported that recorded and calculated lake levels agree within acceptable limits up to the mid-1970s and divergence increased afterwards which was mainly attributed to land use changes. The other most important impact of LULC change is water quality. Water quality in the upper sections of Tikur Wuha River, where there exist forest and woodlands, was better as compared to the lower sections in terms of turbidity, pH, TDS, EC and in the content of ammonia, nitrate and phosphate (Kebede *et al.*, 2014).

While it is evident that there were significant impacts on Hawassa watershed by LULC changes, even minor change in terms of relative spatial extent of a land used class can have significant impact on watershed hydrology (Chu *et al.*, 2010). However, discriminating the impacts of LULC changes on hydrological signals in general still remain an unresolved problem (Sivapalan & Kalma, 1995).

3.4 Morphometry of Lake Hawassa

There are reports that erosion and sedimentation resulted in morphometric characteristics of Hawassa watershed. Lake Hawassa and Lake Cheleleka (partly) are the destinations of eroded materials from the entire catchment owing to their relative elevations. The mean erosion rate of the whole catchment was estimated to be 4.12 Ton ha^{-1} y^{-2} (Eshete, 2009). Tikur Wuha catchment erosion rate was estimated as 3.12 tons per hectare per year by Eshete (2009) and 4.32 tons per hectare per year by Dejen (2016). According to Eshete (2009), though the sub catchments yield varying estimates of erosion rates, the rates were on the rise in all sub catchments. Despite Tikur Wuha sub-catchment had relatively small rate of erosion, the disappearance of Lake Cheleleka and Lake Hawassa level rise was attributed to siltation by many authors (Eshete, 2009; Gebreegziabher, 2005; WWDSE, 2001). This plumps for the importance of bathymetric investigation on Lake Hawassa to analyze the impact of erosion and sedimentation.

Morphometric information of Ethiopian lakes was not available until recently. Nowadays, bathymetric maps have been produced for a number of Ethiopian rift lakes (Ayenew, 2009). The only available bathymetric map of Lake Hawassa is the one produced by WWDSE in 1999 (WWDSE, 2001). The map provided detailed basic morphometric information of Lake Hawassa (see Table 3-1). Development of bathymetric map for 1973 was also attempted in the same study from aerial photos. However, the source and extent of the work that led to the facts was not known and it was not possible for the author to get access to it.

Table 3-1. Morphometric Parameters of Lake Hawassa (WWDSE, 2001)

Period	Elevation (m.a.s.l)	Area (Km^2)	Volume (MCM)	Effective length$_{max}$ (Km)	Length (Km)	Width max (Km)	W mean (Km)	D mean (m)	D max (m)
Jan1973/76	1679.79	92	1152.16	15.75	46.75	8.75	5.84	12.52	21.09
Feb 1999	1681.9	100.0	1356.1	17.1	52.8	9.5	5.8	13.6	23.2

Monitoring lakes for hydrographical changes over time is essential for the management of their ecosystems. Since 1999, the changes that Lake Hawassa had undergone were exhibited in the alteration of its morphologic characteristics. Conducting morphometric studies are evident to substantiate the effect of siltation on the Lake and impact of LULC changes. The maps uncover valuable information for the management and protection of the Lake.

3.5 Hydrologic Modeling in Hawassa Watershed

There are few hydrological investigations on lakes of the Ethiopian rift valley basin. Interests to study Hawassa watershed grew with the lake level rise and the danger imposed upon Hawassa Town (Ayenew & Gebreegziabher, 2006). Water Works Design and Supervision Enterprise assigned by the SNNRS government conducted a study on Lake Hawassa level rise in. This study concluded that open water evaporation is about 164.566 Mm^3 per year, change in storage was about 9.5 Mm^3 per year and outflow from the lake in the form of groundwater is about 71.5 Mm^3/year (WWDSE, 2001).

Gebreegziabher (2005) estimated water balance of the catchment using WTRBLN model and concluded rainfall constitute about 1398 Mm^3, while surface and subsurface runoff and actual ET constitute about 106 Mm^3, 482 Mm^3 and 916 Mm^3 respectively. The average annual water balance of the lake from spreadsheet hydrological model showed that evaporation constitutes about 131 Mm^3 while precipitation, river discharge and net ground out flow water components constituted about 106 Mm^3 and 83 Mm^3 and 43 Mm^3 respectively. In a hydrological modeling study of Lake Hawassa using SWAT it was found out that open water evaporation from the lake surface was about 163 Mm^3 per year, the net ground water outflow from the Lake was about 102 Mm^3/year, and the lake exhibit storage change of 11 Mm^3/year (Solomon, 2011). In a study to see the future impact of Climate Change on water balance of Lake Hawassa using HBV model, Tikur Wuha River flow will decrease by 26.19 mm/year and 30.4 mm/year while Lake evaporation increase by 20.7 mm/year and 136.5 mm/year in the 2030s and 2090s respectively (Solomon, 2011). From groundwater point of view, the western part of the watershed is susceptible to water table fluctuation that the eastern parts while pollution has the case in reverse (Atnafu, 2014). Ayenew et al. (2007) estimated the annual net groundwater outflow from Lake Hawassa to adjacent basins to be 58 Mm^3.

Water resources estimates by different researchers in the watershed indicate that there is wide range of variations, including in the directly or nearly directly measured parameters. For instance, WWDSE (2001) estimated yearly rainfall to be 80.6 Mm^3 while Gebreegziabher (2005), Ayenew et al. (2007) and Daniel (2006) estimated it in the order of 100-106 Mm^3. Another huge difference is in the estimate of Evaporation. Daniel (2006) reported 178.9 Mm^3 while Gebreegziabher (2005) indicated 131 Mm^3 per year. Surface runoff estimates as well are with high variation, ranging from 83 Mm^3

per year according to Gebreegziabher (2005) to 164.6 by WWDSE (2001). These variations require investigations for the adequate resource quantification and management.

Past investigations in the watershed focus either on the surface or groundwater resources. However, in lake ecosystems surface and groundwater resources are integrated and their interaction is not easily captured by the studying of one of them. When coupled with the impact from natural and anthropogenic origin, studying such watersheds require comprehensive hydrological modeling framework.

Distributed physically-based models have the predictive capacity to assess the effect of land use changes on runoff across a range of scales (Refsgaard, 1997). In this study, the MIKE SHE modeling system was utilized to evaluate hydrologic impacts of land use changes in Tikur Wuha River catchment with mixed land uses. MIKE SHE has been widely utilized by many scientists, engineers, and water management personnel around the world (Graham & Refsgaard, 2001; Im *et al.*, 2009; Rahim *et al.*, 2012; Zhang *et al.*, 2008) including the Nile basin decision support system.

CHAPTER 4: TREND AND CHANGE POINT ANALYSIS IN HYDROMETEOROLOGICAL VARIABLES

4.1 Introduction

Intense processes of the water cycle and an increase in the magnitude of precipitation is a reflection of significant increase in air temperatures around the world (Pachauri *et al.*, 2014; Šraj *et al.*, 2016). In the second half of the 20th century, a significant increment in precipitation was observed in northern and central Asia, eastern parts of north and south America, northern Europe and central Sahel while on the contrary, growing drying conditions have been observed in the Sahel, Mediterranean area, southern Africa and southern Asia (Boyles & Raman, 2003; Caloiero *et al.*, 2011; Hamilton *et al.*, 2006; Lebel & Ali, 2009; Lucero & Rozas, 2002; Sharma, 2000). These changes in precipitation amount and pattern may result in the modification of flow regimes of rivers and inland water bodies. Global temperature rise is a significant hydrological process that affect flow regimes by affecting ET and ice melting (Dahal *et al.*, 2019). That was why these variations were considered as indicators of climate change (Williamson *et al.*, 2009).

Engineering studies of water resources development and management depend heavily on hydrological data which should be stationary, consistent, and homogeneous when they are used for analyses or to simulate a hydrological system (Adeloye & Montaseri, 2002; Dahmen & Hall, 1990). Climate change, low-frequency climate variability and human intervention in river basins violate this assumption of stationarity (Bayazit, 2015). A time series of hydrological data may exhibit jumps and trends owing to a change in the amount of systematic error associated with the recording of data or a change in the statistical properties of the time series (Xiong & Guo, 2004). The later can be either natural or man-made. Climate change, anthropogenic changes in river basins such as land use, and low-frequency climatic variability are the main reasons for non-stationarity in hydrological time series (Bayazit, 2015).

Traditionally, modeling properties with the assumption of stationarity required removing trends in the time series which is termed as detrending. Detrending is essential to properly analyze many time series because it prevents a time series from being correlated if correlations are not present, and if correlations do exist, it reveals a genuine correlation functional dependence (Horvatic *et al.*, 2011). In this study, instead of detrending, the time series are sectioned into two homogeneous parts to study the cause of the change. Partitioning the time series by identifying the time of change allows for easy computation of posterior odds induced by the natural and anthropogenic change agents (Perreault *et al.*, 2000a).

Trends and shifts in hydrometeorologic parameters can be distinguished by various statistical and stochastic techniques (Bayazit, 2015). Detecting trend and stationarity in a hydrologic time series may help in understanding the possible links between hydrological processes and global environment changes (Aminikhanghahi & Cook, 2017; Wang *et al.*, 2005). Another important question brought up with the existence of non-stationarity or trend is when the time of change (change point in time) occurred. The objective of change point detection is to identify the state of the process and handle non-stationarity of time series by discovering the change points in addition to its usefulness in modeling and prediction of time series (Aminikhanghahi & Cook, 2017).

Hydrological parameters such as streamflow and lake level in Hawassa watershed have showed tendency of increase in the past few decades (WWDSE, 2001). It was indicated that high level of Lake Hawassa tends to follow moderate to strong El Niño events while Tikur Wuha river discharge exhibited increasing trend (Belete *et al.*, 2017). These low-frequency components of oceanic-atmospheric phenomena can also influence meteorological parameters impacting stream flows. Studies revealed that LULC change in the watershed is one of the causes of variability in hydrological properties (Degife *et al.*, 2019). However, it remains unclear whether the hydrometeorological parameters of the watershed show trends of long-term changes and to what extent climatic and anthropogenic forces or a combination of two account for the changes.

In the light of climate variability and LULC changes, simultaneous analysis of both hydrometeorologic variables and land use dynamics are required coupled with hydrologic scenario simulations (Wagesho et al., 2012). The aim of this chapter is therefore, to detect changes in precipitation, temperature, lake level and stream flow in Hawassa watershed and identify the time of change for further assessment of impacts of climate and land use changes.

4.2 Materials and Methods

This section discusses the data and analysis methods used to determine the consistency, trend and change points in the hydrometeorological time series.

4.2.1 Data and data sources

Hydroclimatic parameters used in this investigation can be broadly categorized as Tikur Wuha streamflow, Lake Hawassa level, temperature, reference evapotranspiration and rainfall of the watershed. Daily observed rainfall data were collected from five stations namely Hawassa, Haisawita, Wondo Genet and Yorba Duwancho for the periods of 1972–2008 (see Table 4-1). Mean, maximum and minimum temperature, wind speed and relative humidity data for Hawassa station was also collected. These data were obtained from the NMA of Ethiopia. Reference evapotranspiration was calculated using the method of FAO Penman–Monteith (Allen *et al.*, 1998).

Table 4-1. Meteorological stations' information

Stations	Elevation (masl)	Longitude (E)	Latitude (N)	Annual Mean Precipitation (mm)
Haisawita	2258	38°33'42"	6°54'7"	994
Hawassa	1703	38°28'59"	7°3'53"	944
Shashemene	1938	38°35'40"	7°11'35"	910
Wondo Genet	1828	38°37'23"	7°2'37"	1145
Yirba Duwancho	2012	38°23'28"	6°55'11"	1119

Tikur Wuha river flow data (both at Tikur Wuha Bridge and Dato village) and Lake Hawassa water level data were collected from the Ethiopian Ministry of Water Irrigation and Electricity. Historical observations were further checked for data gaps and filled using linear interpolation by comparison with adjacent stations. Monthly mean and extreme records were used to better explain fluctuation in hydrometeorological variables.

Accordingly, aggregate rainfall, temperature, streamflow and lake level records were utilized for subsequent analyses.

4.2.2 Analysis methods

Hydroclimatic variables are often subjected to regime shifts that necessitate investigation for stationarity before they are used in simulations and hydraulic studies (Vaze *et al.*, 2010). In this study, a simple visual method was used in addition to statistical methods of checking the stationarity, consistency, normality, independence, homogeneity and long-term trend of the hydrometeorological data. Moreover, times of change of these variables were detected to facilitate further analysis for land use and modeling exercises.

Table 4-2. Summary Statistics of Hydrometeorologic Variables at Hawassa

Variable	Minimum	Maximum	Mean	Std. deviation
Monthly maximum lake level (m)	0.34	3.82	1.84	0.72
Monthly minimum lake level (m)	0.27	3.78	1.73	0.72
Monthly mean lake level (m)	0.31	3.80	1.79	0.72
Monthly maximum Rainfall (mm)	0.00	110.40	23.01	16.68
Monthly total Rainfall (mm)	0.00	243.30	82.10	57.79
Monthly average Rainfall (mm)	0.00	8.11	2.69	1.89
Monthly maximum Temperature (˚C)	24.60	34.00	29.36	2.10
Monthly minimum Temperature (˚C)	-2.80	13.60	8.23	3.01
Monthly mean Temperature (˚C)	16.00	22.35	19.66	1.07
Monthly total ETo (mm)	89.50	189.00	127.46	18.53
Monthly maximum ETo (mm)	3.90	6.80	5.03	0.62
Monthly minimum ETo (mm)	1.60	5.10	3.03	0.75
TWRD monthly mean flow (m^3/s)	0.76	4.02	2.75	0.70
TWRB monthly max flow (m^3/s)	3.36	14.12	6.58	2.33
TWRB monthly min flow (m^3/s)	3.01	13.55	6.1	2.27

TWRB monthly mean flow (m^3/s)	3.15	13.84	6.33	2.3

The series of monthly and annual maximum, minimum and mean values were extracted from the daily discharge, precipitation and temperature records (see Table 4-2). Detecting the trend and stationarity in a hydrologic time series may help to understand the possible links between hydrological processes and global environment changes (Wang *et al.*, 2005).

4.2.2.1 Mass curves analyses

Visual inspections of hydrometeorologic data can reveal valuable information in understanding the variables under consideration. Although it may give indefinite results because of its inability to say which of the variables caused a break in the pattern, comparing the cumulations of one of the variables against the cumulations of a pattern composed of all similar records can give more definite results. Mass and double mass curves are very basic visual analysis tools. A mass curve is a plot of cumulative values against time while a double mass curve is a plot of cumulative values of one variable against the cumulations of another quantity during the same time period. A plot of the two cumulative hydrometeorological time series exhibits a straight line so long as the proportionality between the two remains unchanged, and the slope of the line represents the proportionality (Searcy *et al.*, 1960). Double mass curves are often used to quantify the relative impact of climate (i.e. precipitation) and human activities (i.e. land use) on the change of total streamflow (Gao *et al.*, 2017).

Therefore, in this study, double mass curve analysis was done by plotting rainfall-rainfall pattern and rainfall-runoff relationships to check the consistency of precipitation and flow records. While the existence of breaks in the slope of the plots signify inconsistency, time of the breaks indicate the time of change. This method can also suggest whether or not further statistical analysis is appropriate.

4.2.2.2 Normality and independence tests

While Autocorrelation analysis is used to identify seasonality and trend in time series data, normality test is associated to the null hypothesis that the population from which a sample is extracted follows a normal distribution. Durbin-Watson autocorrelation test was used to check the data's independence (Douglas et al., 2000) whereas Shapiro-Wilk and Anderson-Darling tests were used to check the normality of the series (Razali et al., 2011) even though normality may not be required for trend detection.

4.2.2.3 Homogeneity test

Homogeneity analysis is an important technique to detect the variability of data (Kang & Yusof, 2012). When a time series is homogeneous, it means that the measurements of the data are taken at a time with the same instruments and environments. Four tests were used to test the homogeneity of the hydrometeorological time series. These were, Standard normal homogeneity test (SNHT), Buishand range (BR) test, Pettitt test and von Neumann ratio (VNR) test. Kang and Yusof (2012) have described and elaborated these tests.

4.2.2.4 Trend test and Change-point analysis

Two non-parametric statistical tests were used to detect trend and change point in the annual and monthly time series extracted. Mann-Kendall statistical test is commonly used for trend detection method. It is a rank-based non-parametric statistical procedure that requires no assumptions concerning the underlying statistical distribution of the data. This makes it suited for non-normally distributed and censored data, which are frequently encountered in Hydroclimatic time series (Gao et al., 2011).

The Mann-Kendall (Kendall, 1975; Mann, 1945) test statistic is calculated (Pohlert, 2016):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(X_j - X_k\right) \qquad 4\text{-}1$$

With,

$$sgn(x) = \begin{cases} 1 \ \ if\ x > 0 \\ 0 \ \ if\ x = 0 \\ -1 \ \ if\ x < 0 \end{cases} \qquad 4\text{-}2$$

The mean of S is $E[S] = 0$ and the variance δ^2 is

$$\delta^2 = \left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j\left(t_j - 1\right)\left(2t_j + 5\right) \right\} /18 \qquad 4\text{-}3$$

Where, p is the number of the tied groups in the data set and t_j is the number of data points in the j^{th} tied group. The statistic S is approximately normally distributed provided that the following Z-transformation is employed:

$$Z = \begin{cases} \frac{S-1}{\sigma} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sigma} & if\ S < 0 \end{cases} \qquad 4\text{-}4$$

The Mann-Kendall trend test requires that the observations are independent. Hamed and Rao in 1998 and Yue and Wang in 2004 improved the test to avoid identifying a trend when it is due to the autocorrelation (Hamed & Rao, 1998; Yue & Wang, 2004). Mann-Kendall test performed in this study accounted the autocorrelation in the parameters evaluated.

The non-parametric approach developed by Pettitt (1979) was used to detect change-points in streamflow, lake level and meteorological time-series. This method detects a significant change in the mean of a time series when the exact time of the change is unknown. The non-parametric statistic is defined as:

$$K_T = max\left|U_{t,T}\right| \qquad 4\text{-}5$$

Where,

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn\left(X_i - X_j\right) \qquad 4\text{-}6$$

The change point of the series is located at K_T, provided that the statistic is significant. The significance probability of K_T is approximated for $p \leq 0.05$ with

$$p \cong 2exp\left(\frac{-6K_T^2}{T^3+T^2}\right) \qquad 4\text{-}7$$

4.3 Results and Discussion

Statistical analysis of the variables was conducted on the monthly aggregate data to obtained mean, standard deviation, maximum and minimum aggregate values. The statistical summary for the hydrometeorological variables is as presented previously in Table 4-2.

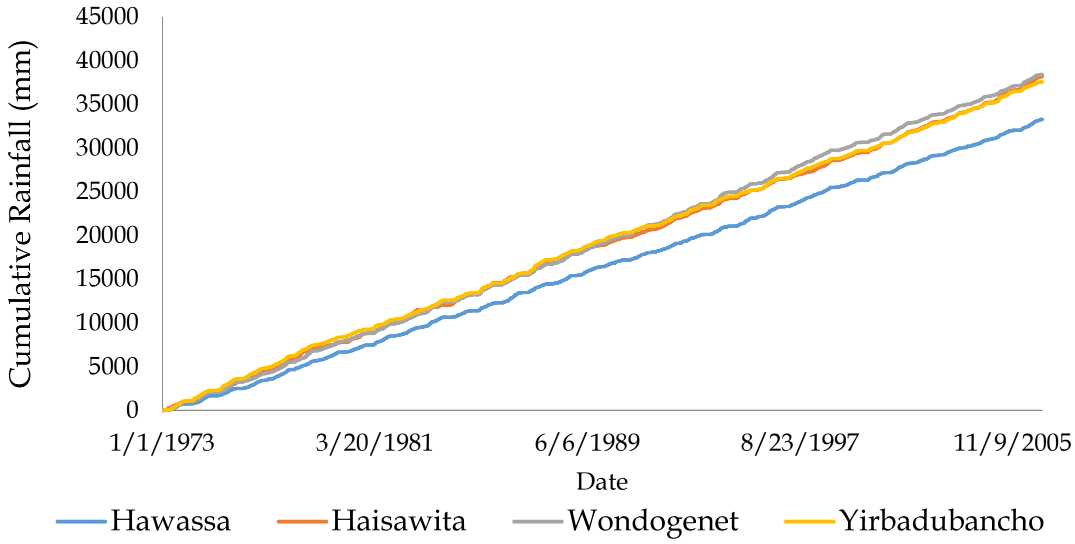


Figure 4.1. Cumulative precipitation at Hawassa, Haisawita, Yirba and Wendo Genet stations

4.3.1 Mass curves analysis

Precipitation data from four stations namely Hawassa, Haisawita, Yirba and Wendo Genet, and Tikur Wuha River flow data were used to create mass and double mass curves to check their consistency. The cumulative curves of rainfall (see Figure 4.1) at each stations presented linear lines with essentially no fluctuation and no obvious convex state.

According to the mass curves of the stations rainfall data, Hawassa received smaller rainfall as compared to the other stations which received higher and relatively similar amounts. Wondo Genet area got slightly higher cumulative rainfall amount. Double mass curves of precipitation at these stations reviled that the precipitations were consistent with unbroken straight lines with slops ranging between 0.92 at Hawassa to 1.06 at Wondo Genet suggesting the records were consistent during the period of analysis. Applications of the double-mass curve to precipitation data revealed that there was no detectable change on the rainfall regime of the study area (see Figure 4.2).

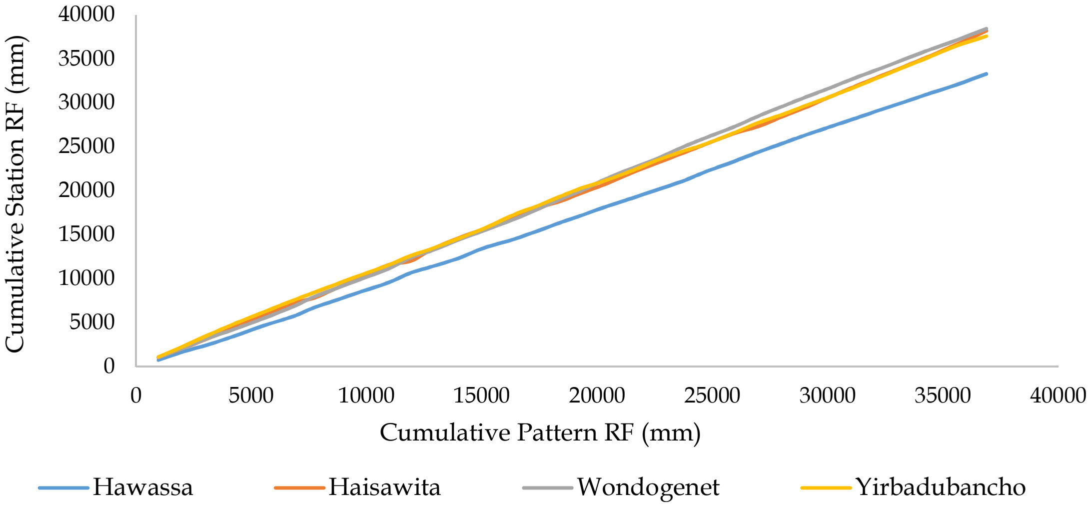


Figure 4.2. Double mass curves of precipitation for stations Hawassa, Haisawita, Wendo Genet and Yirbadubacho versus cumulative rainfall pattern

Nonetheless, double mass curve analysis of rainfall at Hawassa station and discharge at both Bridge and Dato gauges showed inconsistencies unlike the precipitation records.

Double mass curve of Tikur Wuha river discharge at bridge station versus pattern rainfall in Hawassa, shown in Figure 4.3, depicted a break with a slope of 1.83 for the first leg of the line and slope of 2.96 for the second leg. The change point was read from the graph to be in January 1987. This inconsistency was not explained by any historical change of station or any major data observation differences that have occurred in the area. In such cases, it would be wise to make the statistical test for significance.

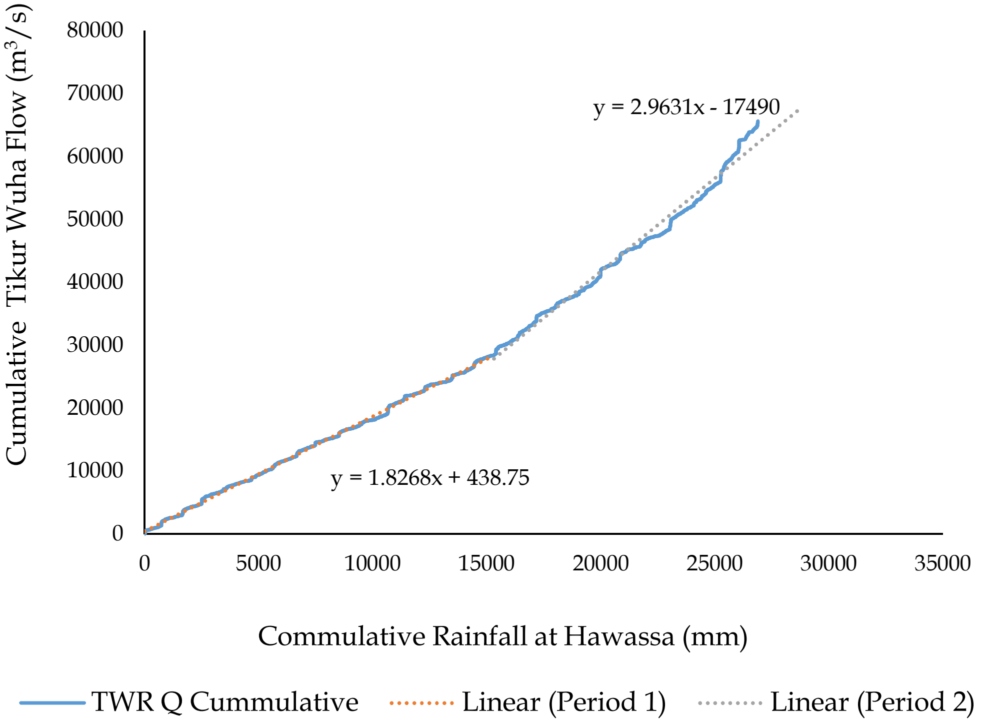


Figure 4.3. Double mass curve of precipitation at Hawassa and Tikur Wuha River flow

4.3.2 Normality and independence tests results

Most of the observations in the monthly (see Table 4-3) and annual maximum, minimum and mean data series followed the normal distribution. However, the Durbin-Watson autocorrelation test indicated a significant autocorrelation in all the annual series.

Autocorrelation test of annual and seasonal (June–September) observed rainfall series of the north and north eastern parts of the RFV lakes basin showed existence of autocorrelation (Wagesho *et al.*, 2012). The same study also indicated that annual average streamflow of Tikur Wuha exhibit statistically significant autocorrelation as found out in the current analysis as well. The existence of autocorrelation was used to guide the choice of trend analysis method.

Table 4-3. Normality and autocorrelation tests p-values for annual time series

(At 5% significant level)

Variable	**Normality Test**		**Autocorrelation Test**
	Shapiro-Wilk	**Anderson-Darling**	**Durbin-Watson**
Lake level max	0.395	0.222	**< 0.0001**
Lake level min	0.589	0.805	**< 0.0001**
Lake level mean	0.550	0.680	**< 0.0001**
Hawassa RF max	**0.000***	**0.006**	**< 0.0001**
Hawassa RF total	0.386	0.560	**< 0.0001**
Hawassa RF mean	0.370	0.547	**< 0.0001**
Hawassa T max	0.055	0.054	**< 0.0001**
Hawassa T min	0.071	**0.017**	**0.0000**
Hawassa T mean	0.135	0.140	**< 0.0001**
TWR mean Flow	**0.000**	**< 0.0001**	**< 0.0001**
TWR max Flow	**0.000**	**0.000**	**< 0.0001**
TWR min Flow	**< 0.0001**	**< 0.0001**	**< 0.0001**

* Significance is shown in bold

4.3.3 Trend Test

Trend and homogeneity test of these variables depicted significant trends also. The non-parametric Mann-Kendall trend analysis result showed maximum, minimum and mean monthly lake level, temperature, ETo and Tikur Wuha discharge exhibited significant increasing trend (

Table 4-4). Similar results were reported previously signifying the upward trend in lake level and Tikur Wuha flow (Belete *et al.*, 2017; Wagesho *et al.*, 2012). Although Belete et al., (2017) showed links between annual rainfall sequential fluctuations and ENSO phenomena, rainfall at Hawassa had no significant trend throughout the recorded study time span. Total, maximum and minimum monthly rainfall in Hawassa station was the only meteorological property consistent, homogeneous and without trend. Average, maximum and minimum annual ETo in Hawassa had a decreasing trend despite temperature's increasing trend. The mean, maximum and minimum annual temperature exhibited an upward trend.

4.3.4 Change point analysis

Pettitt's change point test indicated that change points occurred for monthly aggregates of lake level (1988); reference evapotranspiration (1988 & 1989); temperature (1985, 1990 & 1995); and discharge of Tikur Wuha River (1988) while annual maximum, minimum, mean lake level, mean annual temperature and mean discharge of Tikur Wuha River had change points in the years 1993, 1989, 1989, 1990 and 1986 respectively (see

Table 4-4). Double mass curve analysis indicated that the Tikur Wuha discharge change point was in 1987.

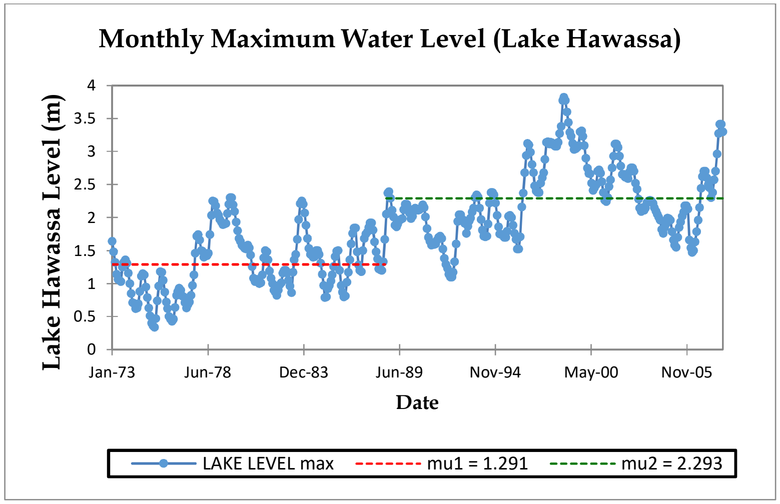
Monthly aggregates of lake level, ETo and Tikur Wuha River flow had change points in August and September 1988, March 1989, July 1988 respectively. Temperature however had November 1985, February 1995 and January 1990 for monthly maximum, minimum and mean temperature series respectively. Change points for hydrometeorological data with detected trend are given in Table 4.4. Generally, results of the change point detection directed that majority of the parameters had changes occurred in the second half of 1988. Trend test and change points analysis on hydrometeorological data are shown in Figure 4.4. Particularly Lake Level, ETo and Tikur Wuha flow had change point in 1988. Consequently, it can be concluded that data 1973-1987 and 1988 to 2003 were homogenous. Since hydrological model development is dependent on river flows partitioning of the study period was based on the year 1988.

Therefore, the trend and change point analysis in hydrometeorological variables of Hawassa watershed gave the basis for evaluating the LULC by minimizing the effect of climate variability on the flow regime of Tikur Wuha. Figure 4.4, on the next pages, shows the trend test and change points on hydrometeorological data.

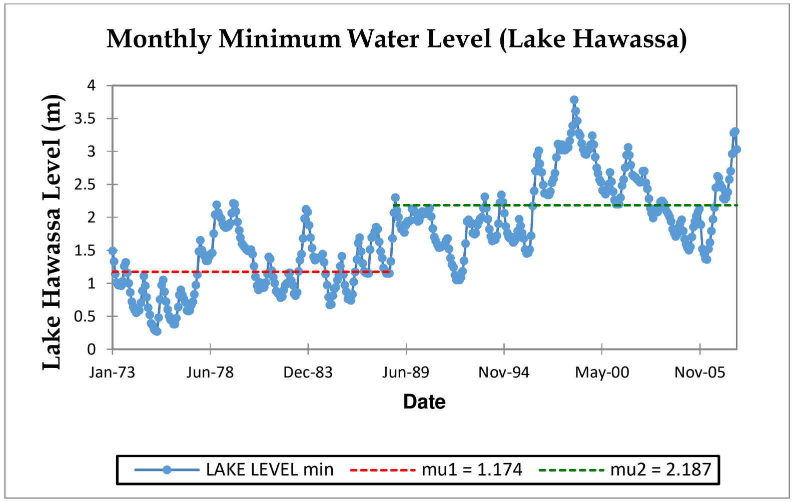
Table 4-4. Trend and time of change in Hydrometeorologic data

Variables	Mann-Kendall test	Pettitt's test	Time of Change
Monthly max lake level (m)	Trend	*	Aug-88
Monthly min lake level (m)	Trend	*	Sep-88
Monthly mean lake level (m)	Trend	*	Aug-88
Monthly max Rainfall (mm)	No Trend	Homogeneous	-
Monthly total Rainfall (mm)	No Trend	Homogeneous	-
Monthly average Rainfall (mm)	No Trend	Homogeneous	-
Monthly max temperature (°C)	Trend	*	Nov-85
Monthly min temperature (°C)	Trend	*	Feb-95
Monthly mean temperature (°C)	Trend	*	Jan-90
Monthly total ETo (mm)	Trend	*	Mar-89
Monthly max ETo (mm)	Trend	*	Mar-89
Monthly min ETo (mm)	Trend	*	Dec-88
TWRD discharge at Dato (m^3/s)	Trend	*	1994
TWRB monthly max flow (m^3/s)	Trend	*	Jul-88
TWRB monthly min flow (m^3/s)	Trend	*	Jul-88
TWRB monthly mean flow (m^3/s)	Trend	*	Jul-88

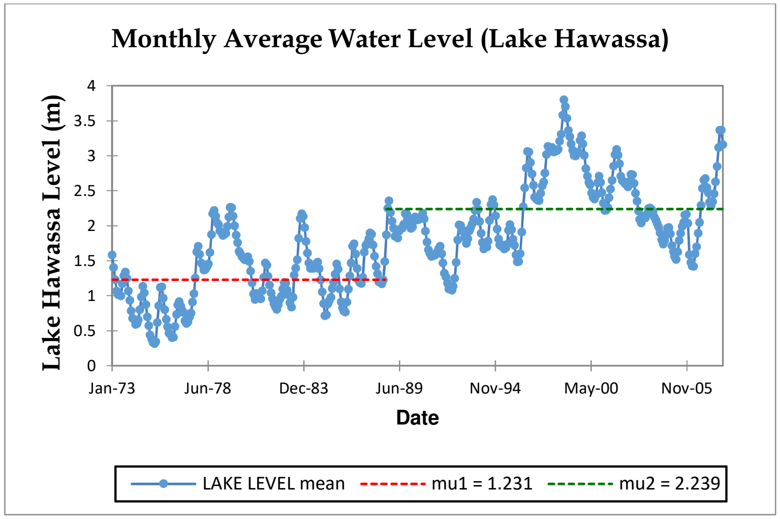
* Non-homogeneous


Monthly Maximum Water Level (Lake Hawassa)
Lake Hawassa Level (m)
4
3.5
3
2.5
2
1.5
1
0.5
0
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
LAKE LEVEL max
mu1 = 1.291
mu2 = 2.293

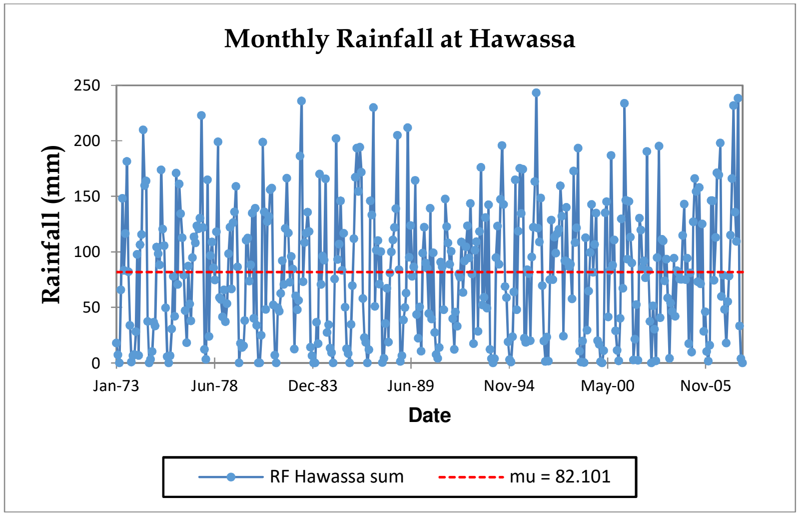
a


Monthly Minimum Water Level (Lake Hawassa)
Lake Hawassa Level (m)
4
3.5
3
2.5
2
1.5
1
0.5
0
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
LAKE LEVEL min
mu1 = 1.174
mu2 = 2.187

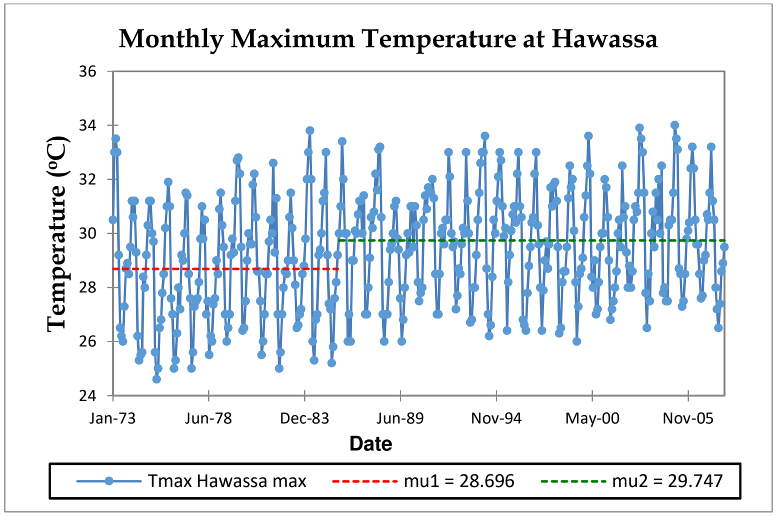
b


Monthly Average Water Level (Lake Hawassa)
Lake Hawassa Level (m)
4
3.5
3
2.5
2
1.5
1
0.5
0
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
LAKE LEVEL mean
mu1 = 1.231
mu2 = 2.239

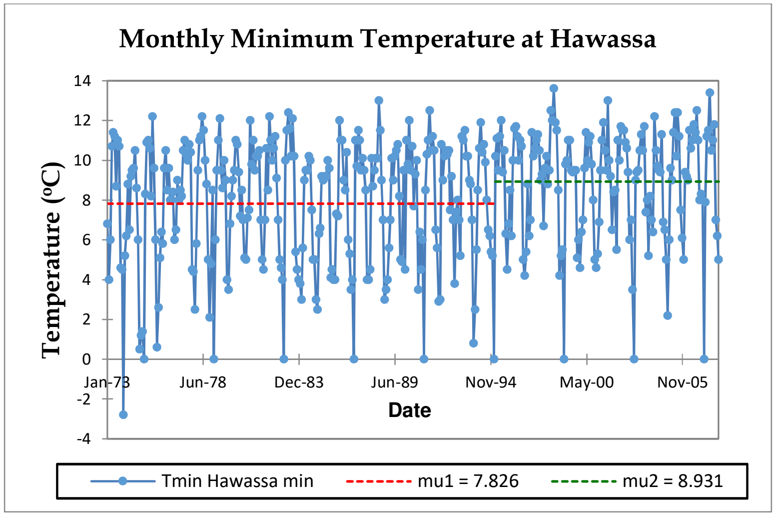
c


Monthly Rainfall at Hawassa
Rainfall (mm)
250
200
150
100
50
0
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
RF Hawassa sum
mu = 82.101

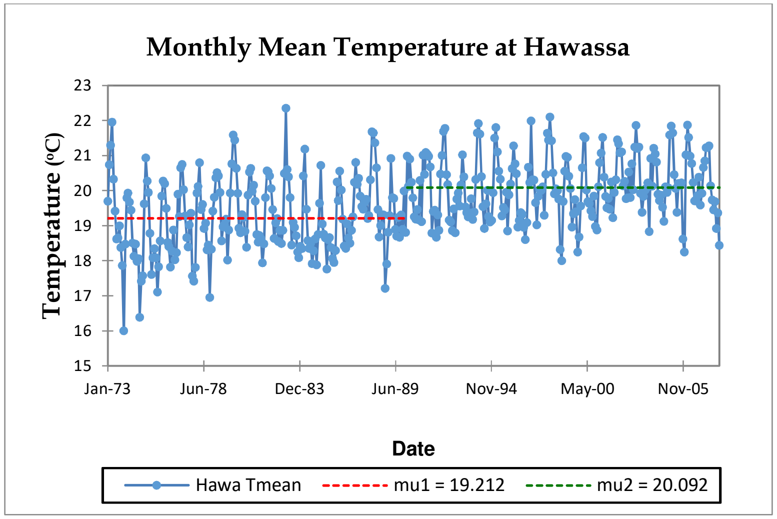
d


Monthly Maximum Temperature at Hawassa
Temperature (°C)
36
34
32
30
28
26
24
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
Tmax Hawassa max
mu1 = 28.696
mu2 = 29.747

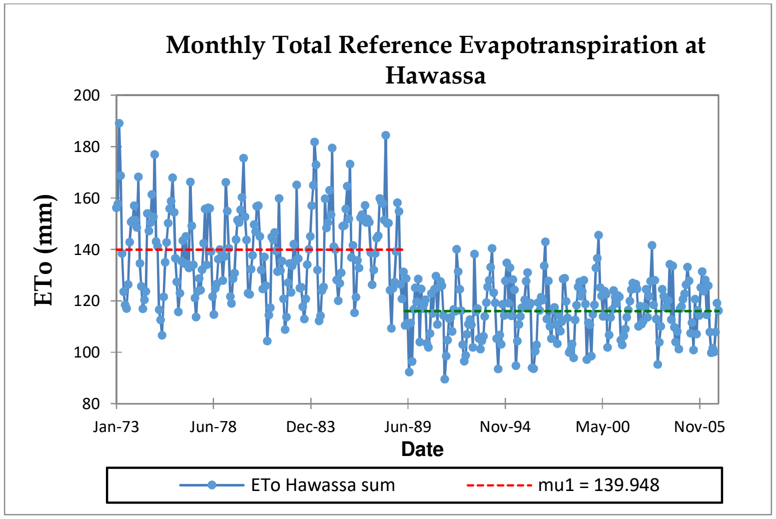
e


Monthly Minimum Temperature at Hawassa
Temperature (°C)
14
12
10
8
6
4
2
0
-2
-4
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
Tmin Hawassa min
mu1 = 7.826
mu2 = 8.931

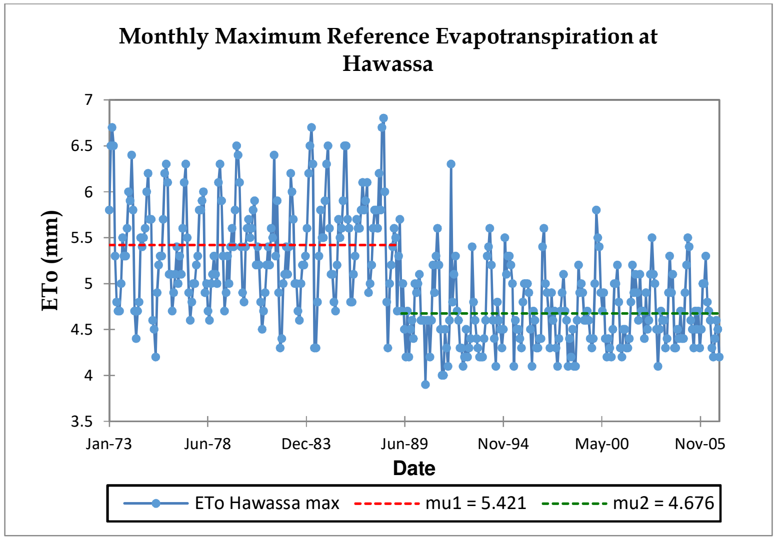
f


Monthly Mean Temperature at Hawassa
Temperature (°C)
23
22
21
20
19
18
17
16
15
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
Hawa Tmean
mu1 = 19.212
mu2 = 20.092

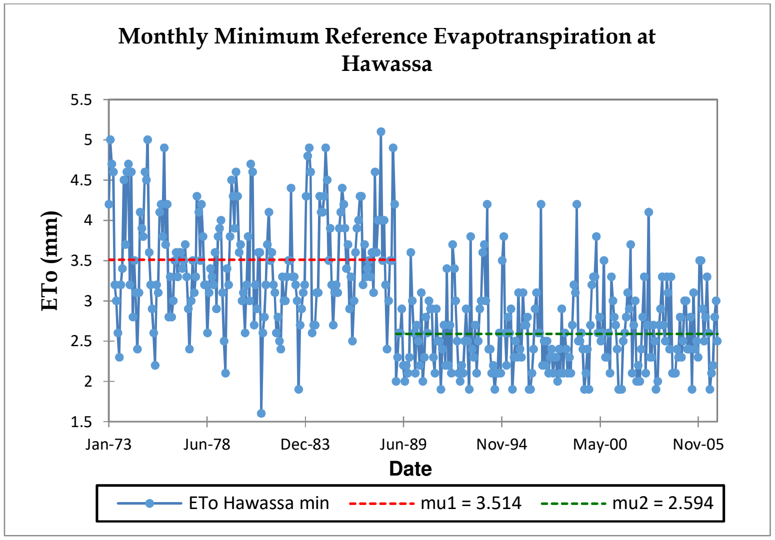
g


Monthly Total Reference Evapotranspiration at Hawassa
ETo (mm)
200
180
160
140
120
100
80
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
ETo Hawassa sum
mu1 = 139.948

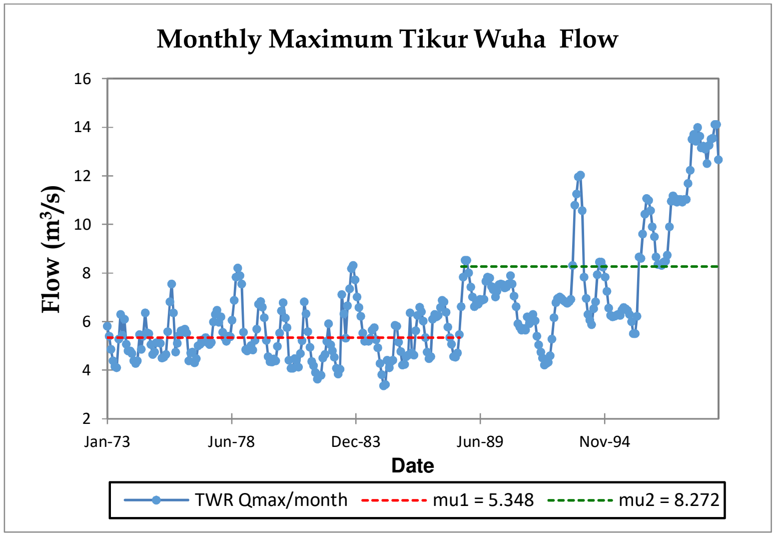
h


Monthly Maximum Reference Evapotranspiration at Hawassa
ETo (mm)
7
6.5
6
5.5
5
4.5
4
3.5
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
ETo Hawassa max
mu1 = 5.421
mu2 = 4.676

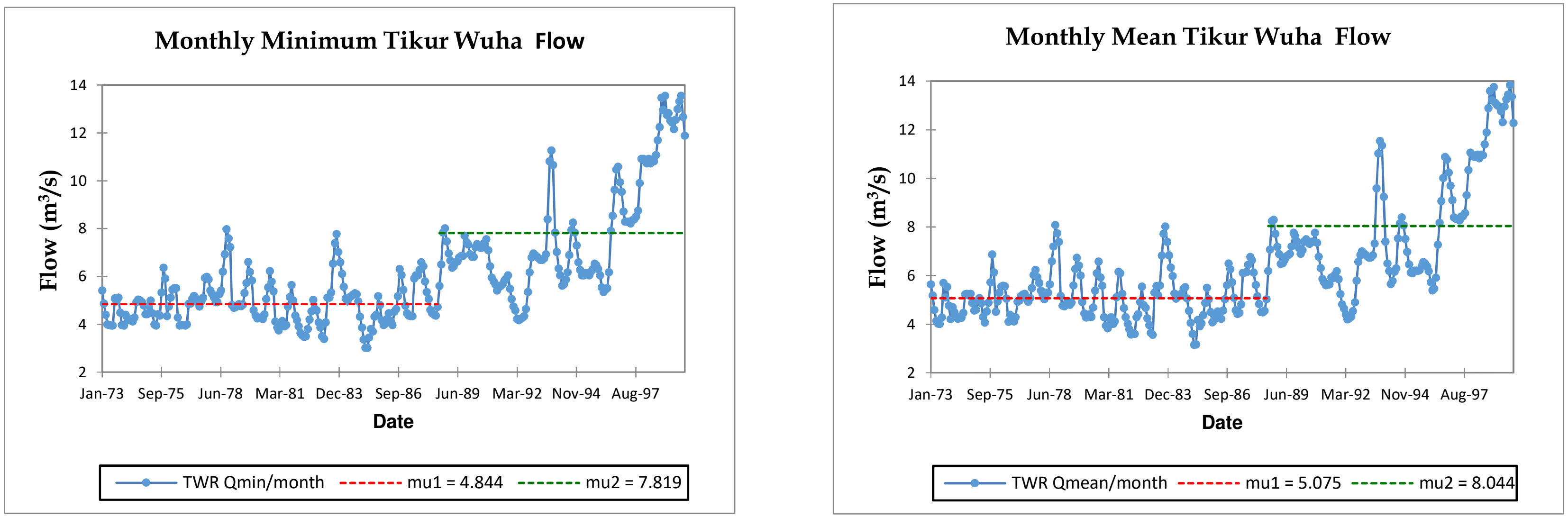
i


Monthly Minimum Reference Evapotranspiration at Hawassa
ETo (mm)
5.5
5
4.5
4
3.5
3
2.5
2
1.5
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
May-00
Nov-05
Date
ETo Hawassa min
mu1 = 3.514
mu2 = 2.594

j


Monthly Maximum Tikur Wuha Flow
Flow (m³/s)
16
14
12
10
8
6
4
2
Jan-73
Jun-78
Dec-83
Jun-89
Nov-94
Date
TWR Qmax/month
mu1 = 5.348
mu2 = 8.272

k



l

m

Figure 4.4. Trend test and change points on hydrometeorological data

(a)(b)(c) Monthly maximum, minimum and mean Lake Hawassa water level respectively

(d) Monthly Rainfall at Hawassa

(e)(f)(g) Monthly maximum, minimum and mean temperature at Hawassa

(h)(i)(j) Monthly total, maximum and minimum ETo at Hawassa

(k)(l)(m) Monthly maximum, minimum and mean Tikur Wuha flow

4.4 Summary and Conclusion

In order to be able to use hydrometeorological data for hydrologic impact assessment, annual and seasonal ETo, streamflow, lake level and temperature events in Hawassa watershed are characterized by visual and statistical methods. As stated in the onset, the aim of this chapter was to detect trends in precipitation, temperature and stream flow data of Hawassa watershed and identify the time of change for further assessment of impacts of climate and land use changes. Some of these parameters showed visible breaks indicating the need for partitioning.

Mass and double mass curve analysis reviled that rainfall had no sign of change in pattern at all stations in the watershed. Tikur Wuha river flow showed a break in patters in 1987. Mann-Kendall trend and Pettitt's change point tests depicted monthly rainfall to be the only homogenous variable. All the rest exhibited non-homogeneity with most common change points in 1988.

Nonetheless, the driving natural and/or anthropogenic causes of the time series remain mystery. Therefore, the origin and quantification of the causes to which the changes are attributed require further investigation. Accordingly, it is apparent that quantifying the impacts of LULC and climate variability by assessing the land use and modeling the hydrological responses is essential to manage the water resources of the watershed. Therefore, based on the findings, selection of images for LULC analysis and choice of period/s for hydrologic model building was made. As a result, Landsat images taken 1973, 1987 and 2003 were selected to study the LULC changes while the period from 1973 to 1987 and 1988-2003 were taken as statistically stationary periods.

It was recommended that the homogenous period spanning from 1973 to 1987 should be used to calibrate and validate the hydrological model. Likewise, the period 1988 to 2003/6 was endorsed to test the impact of climate and LULC changes.

Lastly, such investigations are possible provided that spatially and temporally adequate quality data are available. The type and distribution of hydrometeorological data collection in Hawassa watershed needs to be improved to adequately quantify the water resources, monitor changes and model the resources for improved management and utilization.

CHAPTER 5: LAND USE LAND COVER ANALYSIS

5.1 Introduction

Human activities contribute to significant modifications of hydrology, ecology, geomorphology, climate and biogeochemical cycles (Kattel *et al.*, 2016; Nardi *et al.*, 2018). Among these activities, LULC changes are major environmental modifications that humans exert on the earth. Several studies have indicated the massive conversion of vegetation cover into other land use systems in Ethiopia; one of the most environmentally affected areas being the Central Rift Valley region (Degife *et al.*, 2019). The subject watershed of this investigation is located in this segment of the country.

The landscape of the Hawassa watershed is a direct reflection of the volcanic eruption and intensive tectonic activities in the geological time and modification through erosion processes effected by LULC changes (Abiye, 2008). The suitable weather for farming, growth of industries and tourism, pressure due to peoples' migration and the degradation of natural resources as a result, impacted the watershed characteristics. There are quite a few studies conducted in Hawassa watershed to substantiate the impacts from LULC changes (Abraha, 2007; Degen, 2016; Degife *et al.*, 2019; Eshete, 2009). These studies confirmed the significance of the changes on LULC in the watershed by showing the spatio-temporal aspect of the changes at random times depending mainly on the availability of data and the time of study.

Consequently however, these studies fail to tie the LULC changes to the hydrometeorological changes in the watershed. This in turn makes it difficult to discern the climate and manmade impacts on the watershed. Although many of them were based on arbitrary periods, some identified specific times. For instance, Degife et al., (2019) chose the year 1992 to reflect on the influence of socialist mode of production on land use.

For an endorheic watershed like Lake Hawassa, where rapid hydrologic regime shifts are observed (Belete *et al.*, 2017), studying the LULC change impacts is of paramount importance. Despite the past LULC change investigations however, the changes were not linked with the meteorological and hydrological changes to show the impacts induced. In this study, periods of LULC changes were selected such that times of changes are evidenced by the corresponding hydrometeorological changes. Change point analysis (see CHAPTER 4:) was the basis for the selection of the periods at which the Landsat images were taken.

Tikur Wuha River flow exhibited change between the years 1985 and 1986. Mean annual Lake Hawassa level change point was between the years 1988-1989. If these changes were heavily impacted by the land use changes, it is apparent that the before change and the after change LULC would be different. Therefore, three reference years were selected at the beginning, at the transition times and at the end of the study period i.e. 1973, 1987 and 2003. Additional 2019 image was included to show the recent LULC change of the study area.

Hence, the objectives of this chapter is to investigate the magnitude, and transformation patterns of spatio-temporal LULC transitions between different LULC classes during meteorologically and hydrologically detected change points. In addition, analyzing levels of lakes in the watershed as impacted by the changes will give a perspective.

5.2 Materials and Methods

The following sections discuss the materials and methods used in the study to come up with the LULC maps for the watershed.

5.2.1 Spatial datasets

Landsat images (of 1973, 1987, 2003 and 2019), DEM (SRTM 30 m), topographic maps and field data were used in this study (see Table 5-1. Spatial data types used in the study). Ground control points were collected from topographic maps, other studies, Google Earth images, satellite images and field observation. Catchment delineation was done using the 30 m resolution DEM in ArcGIS environment.

Table 5-1. Spatial data types used in the study

Data type	Spatial resolution	Date captured
Landsat MSS	60 m	1-Jan-1973
Landsat TM	30 m	8-Jan-1987
Landsat ETM+	30 m	1-Dec-2003
Landsat	30 m	16-Jan-2019
Topographic map	1:50,000	1976
DEM (SRTM)	30 m	2000
Field survey/GCPs/		2012-2015

5.2.2 Pre-processing of spatial data

The first three geometrically and radiometrically corrected Landsat images used for this study were acquired from United States Geological Survey (USGS) website (USGS, 2014) in 2014 and the last image was acquired in 2020. The pre-processing of the image data in this study include resizing to the study area, enhancing the image to improve visibility and conversion of the Digital Number (DN) values of the image to Top of Atmosphere (ToA) Reflectance values. The Gain and Bias and sun angle correction methods were used to convert DN values to ToAR (Yale, 2015). In this study, UTM Zone 37 Adindan reference system was used. Therefore, all maps and images were re-projected to this reference coordinate system.

5.2.3 Methods of LULC classification and accuracy assessment

Identification of LULC types on the satellite images was carried out by visual interpretation, previous studies and field visit of the study area. Thus, six classes were identified (see Table 5-2). The identified major LULCs for this study were Built-up Area, Cultivated Land, Grassland, Grassed Wetland, Shrub and Forest land and Water Body. Transformed divergence separability computation technique was used to statistically look at the separability between the identified LULC class-pairs in Erdas Imagine 2014. Attaining the best transformed divergence separability values during the LULC classification phases can provide high probability of getting LULC classes correctly classified. A transformed divergence value of 2,000 suggests excellent between-class separation while above 1,900 provides good separation, and below 1,700 is poor (Jensen, 2015).

Supervised classification with maximum likelihood classifier was used primarily for the image classification. The common tool of assessing the accuracy of image classification used in the study was the error matrix which compares pixels or polygons in a classified image against ground reference data (Jensen, 2015). More than 60 training areas/pixels were used for each class for these purposes. The ground truth data collected from primary and secondary sources were used in the classification and accuracy assessments of the LULC maps. Accuracy assessment reporting for the image analyses made requires the overall classification accuracy to be above 90% (Butt *et al.*, 2015) and kappa statistics above 0.9 (Lea & Curtis, 2010).

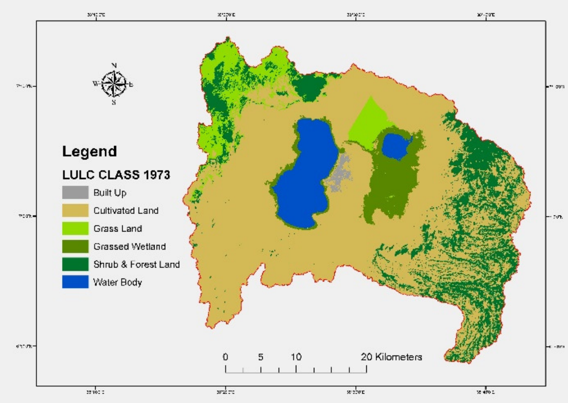
Generalization of classes i.e. post classification simplification was done with ArcMap analysis tools. Majority filter, boundary clean and region group tools of ArcMap were used to remove the misclassified pixels in the classified image, to smooth the boundaries between classes and to identify clusters with class group respectively.

Table 5-2. Descriptions of LULC Classes

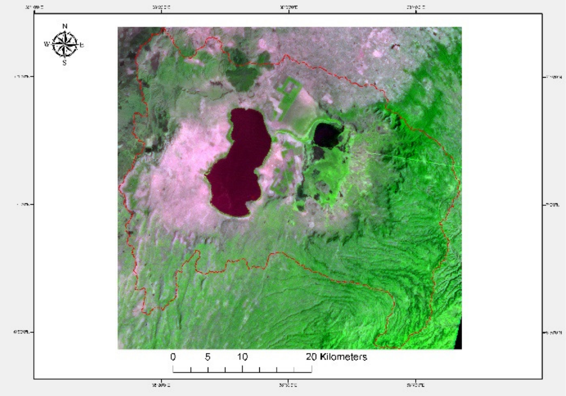
LULC Class types	**Descriptions**
Built up area	Urban residential, commercial, industrial areas and infrastructure developments such as roads etc.
Cultivated land	Areas used for crop cultivation, fallow land mainly bare soil and irrigated fields
Grass land	Area covered with grass which is used for grazing and that remains covered by grass and/or bare soil
Grassed wetland	Former Lake Cheleleka and its swamp, where grass is growing
Shrub and Forest land	areas covered with eucalyptus, junipers trees and mixed with indigenous species of trees and shrubs
Water bodies	Lakes and reservoirs

5.3 Results and Discussion

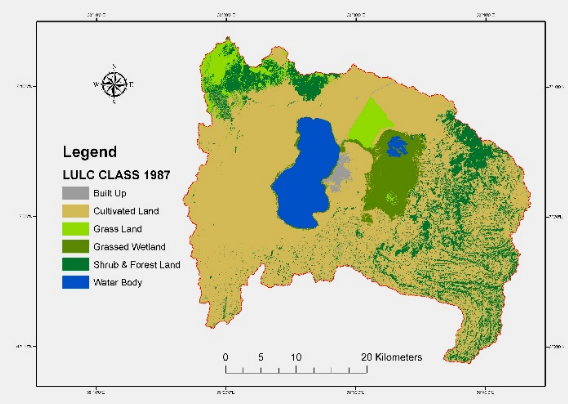
Following all the pre-processing procedures, the training data for each class were tested for separability. Satisfactory transformed divergence separability value of 1987.8, 1996.9, 1998.0 and 2000 were found for 1973, 1987, 2003 and 2019 Landsat images respectively. The classified LULC map of Hawassa watershed for the years 1973, 1987, 2003 and 2019 is given in Figure 5.1.



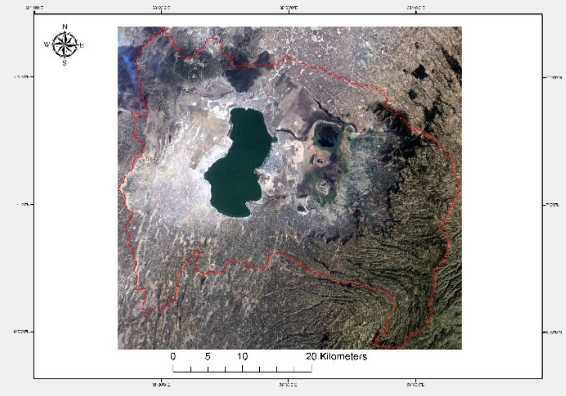
1973 LULC classification



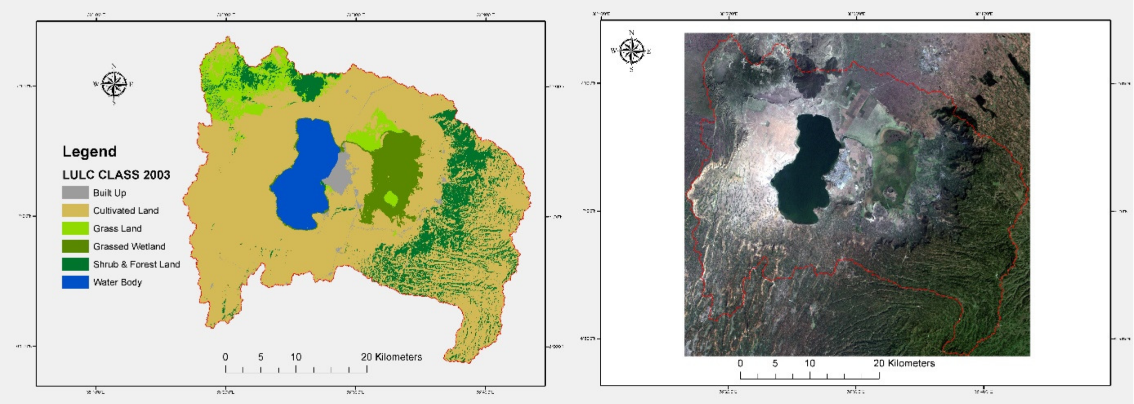
1973 Landsat Image



1987 LULC classification

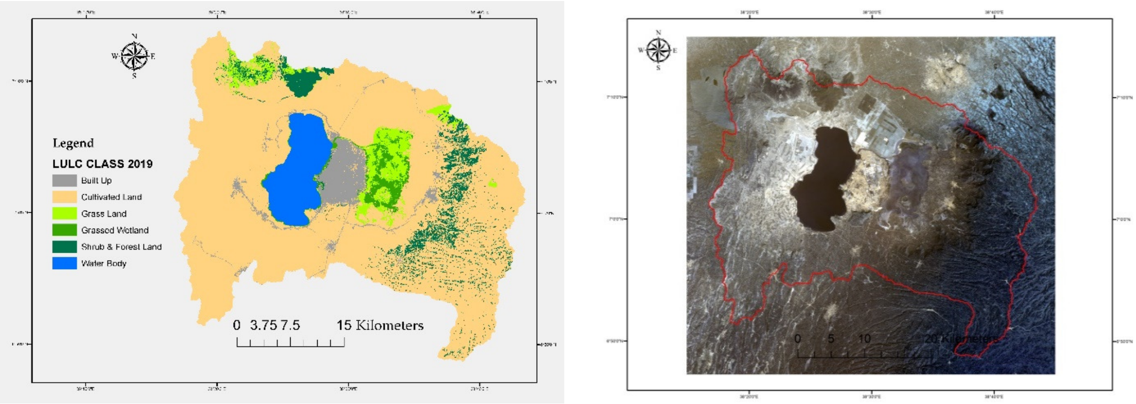


1987 Landsat Image



2003 LULC classification

2003 Landsat Image



2019 LULC classification

2019 Landsat Image

Figure 5.1. Land use land cover classification of Hawassa watershed for 1973, 1987, 2003 and 2019 Landsat images

Supervised image classifications were performed on the four Landsat images in Erdas Imagine 2014. Accuracy assessment successfully achieved the requirements of the overall classification accuracy and kappa statistics values of 90% and 0.9 respectively in these analyses.

Table 5-3 Supervised classification overall accuracy and kappa coefficient of Landsat Images

Landsat Images	**Accuracy assessment**	
	Overall accuracy	**Kappa coefficient**
1973	89.47%	0.87
1987	95.56%	0.95
2003	92.50%	0.91
2019	95.13%	0.94

The accuracy and kappa coefficient of the 1973 image was lower than the rest due to fewer bands and courser resolution it has. While the overall accuracy and kappa coefficient of these image classifications are given in Table 5-3, Appendix II shows the confusion matrixes for each classified image.

5.3.1 Land use land cover change in Hawassa watershed

Land use land cover classifications of Hawassa watershed for the reference years' images and the recent image in 2019, as shown in Figure 5.1, are evident for the level of LULC changes occurred and occurring.

Dramatic increase of 188% in built-up area was seen in the watershed, and about 114% of this change happened between the years 1987 and 2003 (see Table 5-4). This estimate was also supported by other research reports in the area (Wondrade *et al.*, 2014). Although this LULC class showed the highest increase, it was still the smallest in area coverage, accounting only about 1.5% of the total area in 2003.

Table 5-4. Land use land cover changes in Hawassa watershed (1973-2003)

LULC	Area (Sq.km)			% Change		
	1973	**1987**	**2003**	**1973 - 1987**	**1987 - 2003**	**1973 - 2003**
Built Up	7.3	9.8	21.1	34.1	114.8	188.0
Cultivated Land	866.6	922.9	925.0	6.5	0.2	6.7
Grassland	106.2	64.0	92.8	-39.7	44.9	-12.6
Grassed Wetland	83.0	77.7	79.5	-6.3	2.3	-4.2
Shrub & Forest Land	221.8	210.4	171.3	-5.2	-18.6	-22.8
Water Body	96.3	96.4	91.6	0.0	-4.9	-4.9

The largest land use class conversion accounting for over 18.5% between the years 1973 and 1987 was shrub and forest land. This class also exhibited the largest overall class conversion by nearly 23% to other forms of land use during the study period. Grassland seemed to have lost coverage by 39% in the years 1973–1987 and later gained 45% (1987-2003). Even though there was gain in area in Grasslands, the land use diminished in the later years. Cultivated land area increased by 6.7% during the 1973-2003. Although the percentage increases for Cultivated LULC class seem small, area wise it was the highest.

However, unlike grasslands, cultivated land increased at a higher rate between the years 1973 and 1987 than between the years 1987 and 2003. Although the percentages seem to be small as compared to other classes, since the area covered by agriculture is huge, the area converted to cultivation (58.3 km2) is greater than the increase in the other classes. Water body in the watershed showed a decrease in wetlands and Lake Cheleleka while Lake Hawassa gained surface area. The LULC classification indicated the net gain and loss of water bodies till 1987 was negligible. After 1987, water body in the watershed decreased by almost 5%.

5.3.2 Land use land cover change in Tikur Wuha River watershed

Tikur Wuha river catchment is the only gauged sub watershed in Hawassa watershed. Quantifying the LULC changes in this sub watershed is essential for further water resources management studies. Therefore, detail LULC change analysis was done for this catchment to be input to the hydrological assessment for the years 1973, 1987 and 2003 (see Figure 5.2).

A steady increase in cultivated land (about 11 km^2) and uniform decrease in water bodies (about 5.5 km^2) were witnessed during the study period. Lake Cheleleka has been steadily decreasing to extinction while its wetland and grassland increased nearly steadily in the selected time spans. Dry grass land generally increased, but was more significantly raised during 1987 to 2003. The highest LULC change occurred in shrub and forest lands. More than 28 square kilometer shrub and forest land was converted into other land use forms. Nearly 60% of this decrease had happened during 1987 to 2003. The dominantly cultivated Tikur Wuha River catchment has considerable forested land in the Eastern side.

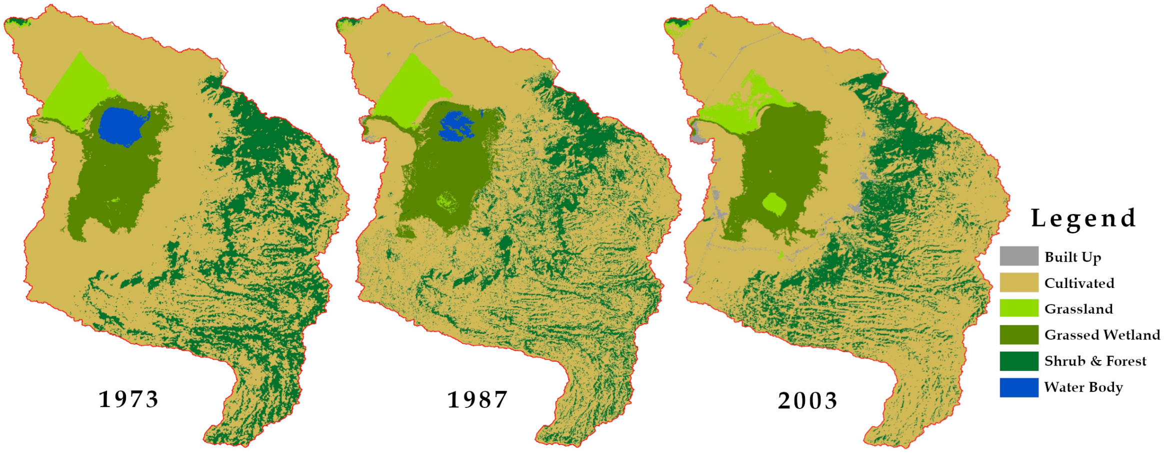


Figure 5.2. Land use land cover classification of Tikur Wuha river watershed for 1973, 1987 and 2003 Landsat images.

Dramatic increase in built-up area was seen also in Tikur Wuha catchment. However, much of it happened between 1987 and 2003. A steady increase in cultivated land was as well witnessed during the study period. Dry grass land generally increased, but was more significant during 1987 to 2003. The catchment encountered highest LULC change in shrub and forest lands. Over 28 square kilometer shrub and forest land was converted into other land use forms. Nearly 60% of this decrease had happened during 1987-2003. Lake Cheleleka has been steadily decreasing to extinction while its wetland and grassland increased nearly steadily as discussed in Hawassa watershed's LULC change. Loss of Lake Cheleleka contributed to the decrease of water body in the catchment (see Table 5-5).

Table 5-5. Land use land cover changes in Tikur Wuha watershed

LULC	Area (Sq.km)			% Change		
	1973	1987	2003	1973 - 1987	1987 - 2003	1973 - 2003
Built Up	0.35	1.37	6.37	290	364.5	1711.3
Cultivated Land	446.39	459.05	476.65	2.8	3.8	6.8
Grass Land	25.16	24.49	20.61	-2.7	-15.9	-18.1
Grassed Wetland	67.12	71.8	74.81	7	4.2	11.5
Shrub & Forest Land	165.56	153.32	137.26	-7.4	-10.5	-17.1
Water Body	11.12	5.66	0	-49.1	-100	-100

Hawassa basin has undergone a significant LULC changes from dominantly forested contributing watersheds, 51.6%, to dominantly agricultural, 41.46% (Abraha, 2007). Daniel (2010) indicated that that natural vegetation in the catchment decreased by 9.06% between years 1965-1998. Over the past few decades the Hawassa city metropolitan has also expanded tremendously to the level it may affect the runoff processes and waste influent to the Lake. These changes have impacted not only the hydrology but also the ecology of the catchment. Literature indicates that the ecosystem of the basin functioned well before the unwise intervention of citizens, especially the emergence and expansion of Hawassa town (Lemma, 2005).

5.3.3 Recent LULC change in Hawassa watershed

The 2019 LULC map had the purpose of giving insight to the recent past conditions of the watershed. Consequently, Table 5-6 shows rate of change of LULC with respect to 2019 map. Built up LULC class has further increased in area by about 803% from that of 1973. Cultivated land class also increased by about 21%. Area coverage wise though cultivated land is still with the highest increase (178 sq. km). The rest of the LULC classes decline, Grassed Wetland being the most deteriorated class. Next to it, comparably equal, was Shrub and Forest LULC class. Grassland lost 36.7% in 2019 than the 1973 cover.

Table 5-6 Comparison of 2019 LULC with 1973, 1987 and 2003

LULC	Area Change (Sq. Km)			% Change		
	1973 - 2019	1987 - 2019	2003 - 2019	1973 - 2019	1987 - 2019	2003 - 2019
Built Up	58.9	56.4	45.1	802.9%	575.3%	213.7%
Cultivated Land	178.0	121.7	119.6	20.5%	13.2%	12.9%
Grassland	-39.1	3.5	-25.3	-36.7%	5.5%	-27.3%
Grassed Wetland	-53.0	-47.7	-49.5	-63.9%	-61.4%	-62.3%
Shrub & Forest Land	-138.9	-127.5	-88.4	-62.6%	-60.6%	-51.6%
Water Body	-5.3	-5.3	-0.5	-5.5%	-5.5%	-0.6%

The loss of water body LULC class was primarily the loss of Lake Cheleleka in 2003. The fact that Lake Hawassa declined by only 0.6% in the past 15 years (2003-2019) may seem to be alright when seen lightly. Nevertheless, it indicated that the Lake is endangered for extinction in the extended future unless measures are taken to protect it.

5.3.4 Land use land cover change impacts on Lake Hawassa level

To look at the impact of LULC change on the level of Lake Hawassa, the lake level data was sectioned into the homogeneous periods (1973-1987, and 1988-2003) and the following period (2004-2016). The graph of the sectioned lake level (see Figure 5.3) shows a cyclic fifteen years pattern happening in 1979-1980, 1995-1996 and 2011-2012 regardless of the land use change. The time axes in Figure 5.3 indicate the month and year from the onset of the periods. The average lake levels for the periods specified above were 1.2 m, 2.2 m and 2.4 m respectively. This shows that there was, on average, one meter level rise during the homogeneous periods.

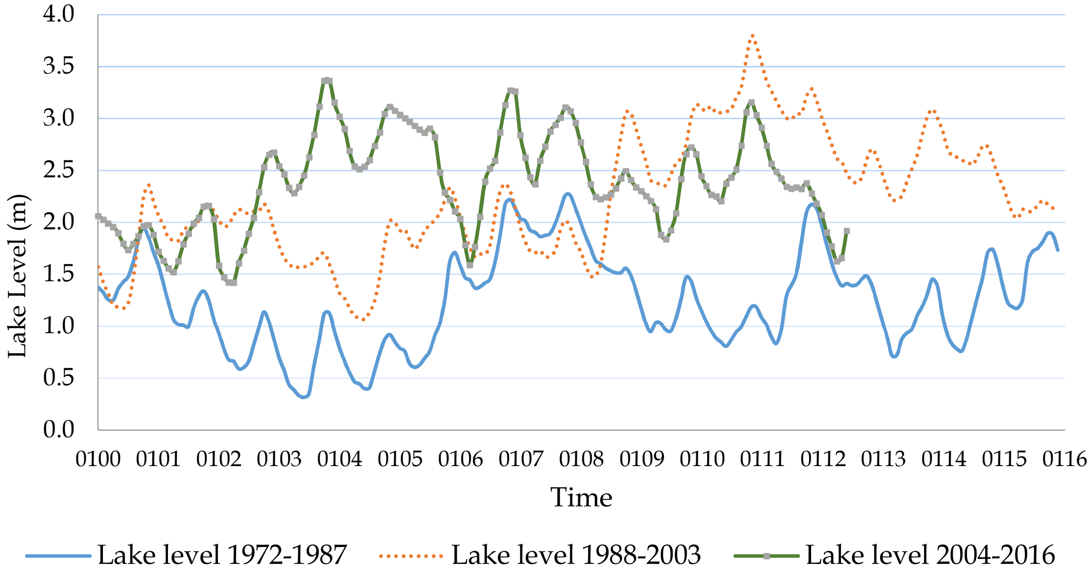
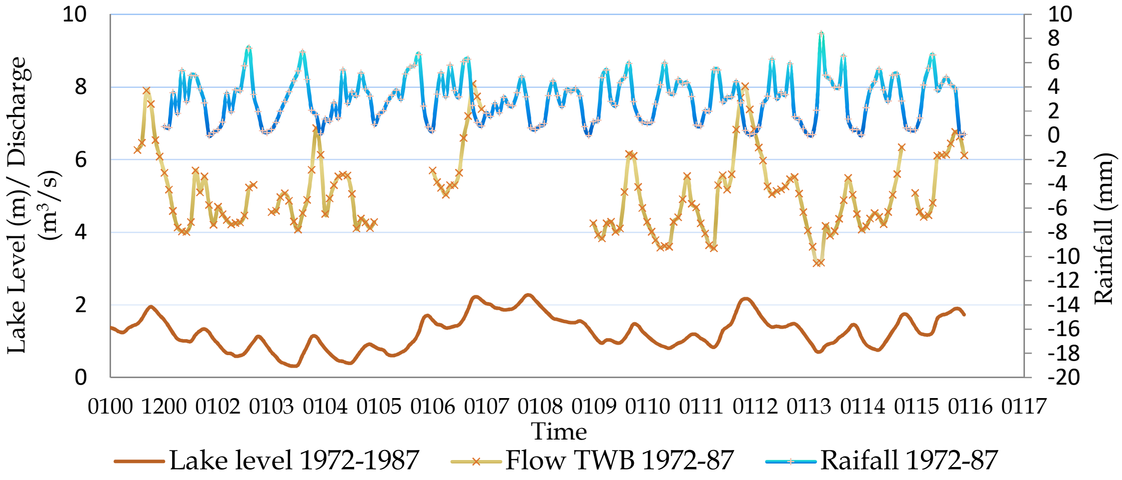


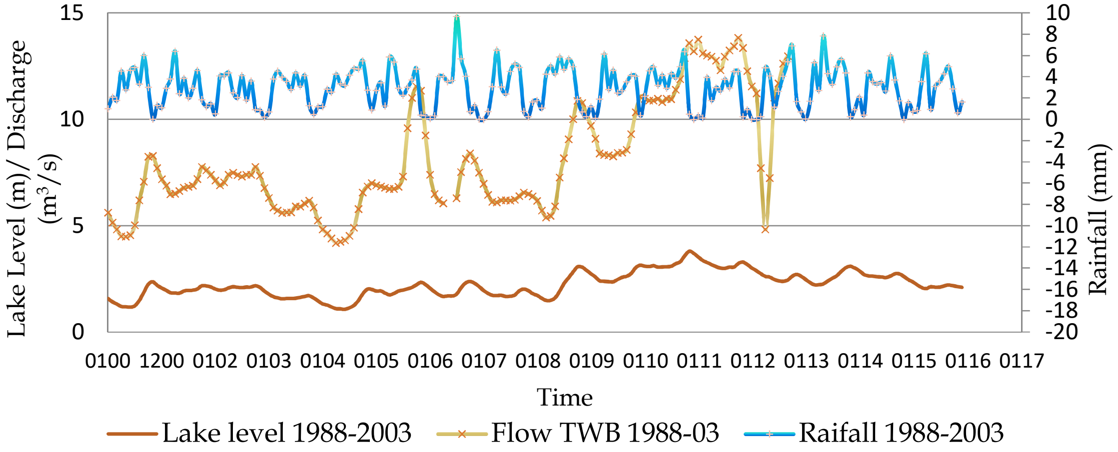
Figure 5.3 Level of Lake Hawassa sectioned into three periods (1973-1987, 1988-2003 and 2004-2019)

On one hand, the LULC changes were dominated by cultivated land which favored surface flow. Likewise, urban areas which are on a rise at an alarming rate also aid surface flow towards the Lake. On the other hand, the declining LULC classes such as Shrub and Forests, which used to favor surface detention and percolation, contributed to the rising level in Lake Hawassa. When comparing Lake Hawassa level, average watershed rainfall and Tikur Wuha River discharge per the described period (see Figure 5.4), similar patterns were seen. These were the reflections of the LULC change impacts on the watershed.



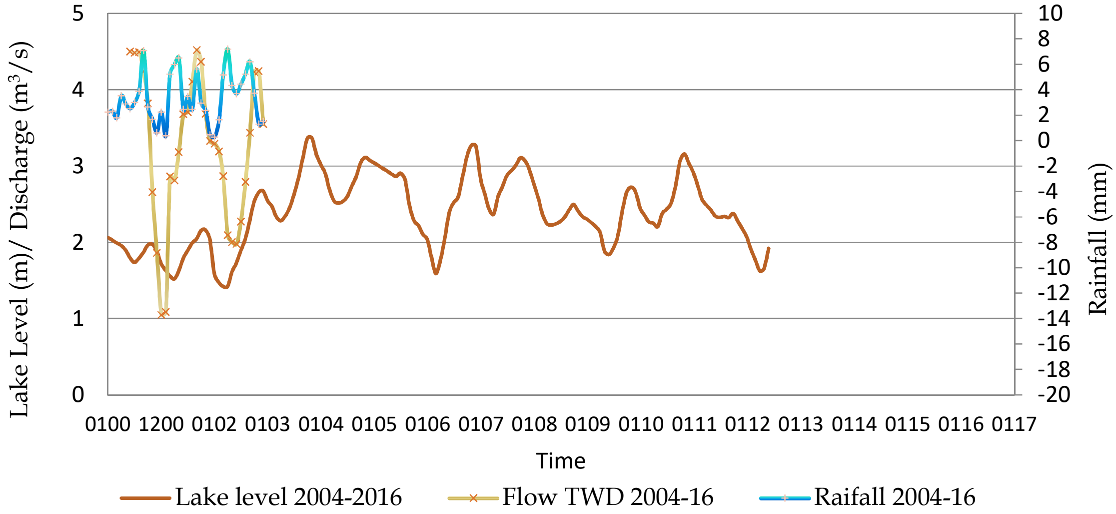
Lake Level (m)/ Discharge (m^3/s)
Rainfall (mm)
10
8
6
4
2
0
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0100 1200 0102 0103 0104 0105 0106 0107 0108 0109 0110 0111 0112 0113 0114 0115 0116 0117
Time
Lake level 1972-1987
Flow TWB 1972-87
Raifall 1972-87

(a)



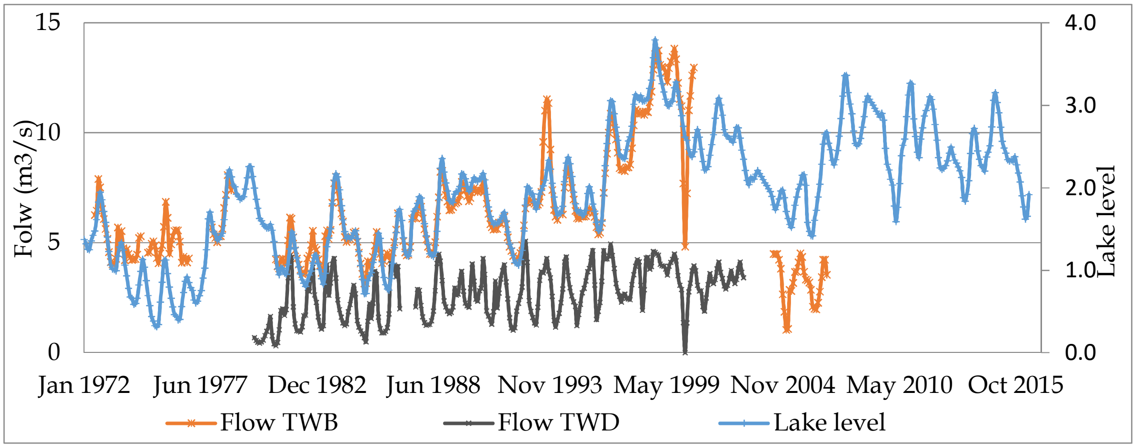
Lake Level (m)/ Discharge (m^3/s)
Rainfall (mm)
15
10
5
0
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0100 1200 0102 0103 0104 0105 0106 0107 0108 0109 0110 0111 0112 0113 0114 0115 0116 0117
Time
Lake level 1988-2003
Flow TWB 1988-03
Raifall 1988-2003

(b)



Lake Level (m)/ Discharge (m^3/s)
Rainfall (mm)
5
4
3
2
1
0
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0100 1200 0102 0103 0104 0105 0106 0107 0108 0109 0110 0111 0112 0113 0114 0115 0116 0117
Time
Lake level 2004-2016
Flow TWD 2004-16
Raifall 2004-16

(c)



(d)

Figure 5.4 Lake level, Tikur Wuha river discharge and Hawassa watershed average rainfall patterns (a) For the period 1972-1987 (b) For the period 1988-2003 (c) For the period 2004-2016 (d) Flow at Bridge and Dato stations, and Lake Hawassa level

For instance, Tikur Wuha river discharge at Bridge station (TWB) has similar pattern with lake level especially during 1988-2003. Tikur Wuha river discharge at Dato station (TWD) also follow reasonably analogous pattern with the lake level.

5.4 Conclusion and Recommendation

According to change point analysis of hydrometeorological time series (see CHAPTER 4:), Hawassa watershed exhibited changes mainly between the years 1986 and 1988. If these changes were heavily impacted by the LULC changes, it is apparent that the before and the after LULC changes would be different. Therefore, three Reference year satellite images for LULC analysis were selected (i.e. 1973, 1987 and 2003). The 2019 image was added to assess the recent conditions of the LULC of the study area. Land use and land cover maps were derived from satellite imagery and ground truthing (surveying and secondary data) by supervised image classification technique. The image analyses clearly showed the six major LULC types in the Hawassa watershed namely Cultivated Land, Shrub and Forest Land, Built up Area, Water Body, Grass Land and Grassed Wetland.

It was shown that the watershed experienced rapid LULC changes since the 1970s. The most dominant change was conversion to cropland. Urbanization induced by peoples' migration and resettlement to Hawassa town and surrounding areas in the form of residential, industrial and military facilities was one of the most rapidly growing LULC classes. Within three decades (1973-2003) Built up areas increased by more than 188%. In 2019 this figure was raised to above 800%. Water body, Grassland, Shrub and Forest land and Grassed Wetlands generally declined in coverage by 5.5%, 36.7%, 62.6% and 63.7% respectively during the study period (1973-2019). These changes were reflected on the level of Lake Hawassa significantly. The lake level showed a 15 year cycle given the homogeneous periods partitioned.

Therefore, this study concluded that the LULC maps produced can be used as an input to hydrological impact assessment study (see CHAPTER 7:). The results supported the hypothesis that hydrological changes (increases in surface runoff, streamflow and lake level rise) were attributed to the conversion of LULC classes. These conversions were from those favoring surface water detention and percolation such as shrub and forest to those favoring surface runoff (cultivated land). Hence, proper land management on cultivated land will positively impact the adverse effect of runoff.

CHAPTER 6: LAKE HAWASSA MORPHOMETRIC CHANGES

6.1 Introduction

Lakes are among the most fragile environments caused by anthropogenic influences alongside natural phenomena that can trigger rapid changes to their ecosystems. Surface area and capacity modifications not counting water quality alterations are manifestations of change in lakes. Soil erosion and sediment deposition as well as pollution from municipal, industrial and agricultural waste are among the major menaces to which lakes are exposed (Ławniczak *et al.*, 2011). The variation in the water quality may depend on the size and shape of the water body, the geologic formation of the lake and the dynamics in the contributing watershed of the lake. Since lakes and reservoirs are low points in the landscape, they receive water and sediment inputs from the surrounding terrestrial catchment and the upwind airsheds (Williamson *et al.*, 2009). Severe erosion and sedimentation may result in diminishing lake size and in some cases, can cause the disappearance of a lake body and induce changes in its fauna and flora population. These inputs can influence the environs positively or negatively and bring about environmental change resulting in the alteration of limnological, hydrological and morphometric characteristics. Therefore, lakes are important sentinels of environmental variations due to the integration of changes in the surrounding landscape and atmosphere; declining lake levels were indicative of climate-driven changes, for instance (Adrian *et al.*, 2009; Legesse *et al.*, 2004; Williamson *et al.*, 2009).

Lake Hawassa and the adjoining smaller Lake Cheleleka, like most ERV lakes, have been subjected to natural and anthropogenic alterations. In the 1960s, the rise in the levels of ERV lakes were apparently related to lake-level changes throughout East and Central Africa due to climate variability (Makin *et al.*, 1975). However, the recent level rise in Lake Hawassa has been attributed to land-use changes in the watershed (WWDSE, 2001) and possibly to climate change (Belete *et al.*, 2017). The geology of Lake Hawassa catchment is characterized by rift system faults and cracks. It was reported that between 1996 and 1998 new cracks were formed on the western side of Lake Hawassa (Ayalew *et al.*, 2004) which may influence groundwater flows thereby affecting lake levels. A number of studies have also explored the role of recent land-use and land-cover changes on rising Lake Hawassa levels (Abiye, 2008; Gebremariam, 2002; Lemma, 2005; Tilahun, 2006; WWDSE, 2001). Natural forests on the Wondo Genet escarpments have been under continued threat by human settlement and associated farm expansion, especially since 1990 (Gebremariam, 2002; Lemma, 2005). It was also indicated that the natural vegetation in the watershed decreased by about 9% between the years 1995–1998 (Shewangizaw, 2010). In addition, point and non-point pollution sources from agriculture, industries and municipal waste had affected the quality of groundwater resources in the watershed (Abiye, 2008).

The importance of lake morphology study is not only to understand spatial change in the shape and size of the lake, but also helps to comprehend its hydrologic and limnologic characteristics (Hakanson, 1981; Sandwell & Smith, 2000; Schäfer *et al.*, 2014). Historical morphometric studies in general provide information on spatial and temporal changes in erosion and sediment deposition in addition to changes in bathymetric characteristics. This information can be used to study and remedy the implications on both physical and biological systems (Foxgrover *et al.*, 2004; Fregoso *et al.*, 2008; B. Jaffe & Foxgrover, 2006; B. E. Jaffe *et al.*, 2007; B. E. Jaffe *et al.*, 1998; D. M. Thompson *et al.*, 2015).

Until recent years, morphometric information of Ethiopian lakes was not available. Lake Zeway was the only Rift Valley lake for which a bathymetric map was developed in 1992 (Awulachew, 2006). In recent years, bathymetric maps had been established for a number of Ethiopian rift lakes (Ayenew, 2009). Despite the various investigations on Ethiopian lakes, monitoring these ecosystems for hydrographical changes over time is still lacking. The first extensive hydrographic survey of Lake Hawassa was conducted in 1999 by the Water Works Design and Supervision Enterprise (WWDSE) as part of a study to identify the cause of a rise in Hawassa Lake's level and flooding of Hawassa Town. The environmental changes that Lake Hawassa and Lake Cheleleka had undergone were exhibited in the alteration of their morphologic characteristics. Therefore, studying the morphometric changes uncovers valuable information for the management and protection of the lakes.

Monitoring changes in major Ethiopian lakes that require frequent bathymetric surveys has always been a challenge due to cost and technology-related limitations. These limitations resulted in fewer research dedicated to studying morphometries. With recent advances in remote-sensing and geographic information system (GIS) technology, morphometric studies and bathymetric mapping have become more feasible. This study aims (1) to detect surface area changes in Lake Hawassa and Lake Cheleleka in 1985, 1999 and 2011; (2) to detect morphometric changes, based on the comparison of bathymetric maps for 1999 and 2011; and (3) to estimate the rate and extent of water loss and sediment build up in Lake Hawassa by employing progresses in geostatistics, portable sonar sounding, the global positioning system, and remote-sensing and GIS software analysis tools.

6.2 Materials and Methods

In this study, spatial and bathymetric changes of Lake Hawassa and Lake Cheleleka were investigated in Hawassa watershed. While spatial changes were explored for Lake Hawassa and Lake Cheleleka in 1973, 1985, 1987, 1999, 2011 and 2019 morphometric changes in 1999 and 2011 were examined for Lake Hawassa.

6.2.1 Data used in the analyses

Primary data were obtained by rapid bathymetric surveying using SonarMite echo-sounder (235 kHz frequency, 0.3–75 m depth capacity and +/− 0.025 m accuracy), eTrex Venture Garmin (Garmin Corporation, Taiwan) global positioning system (GPS) and a motorized boat to measure lake depth at uniform grid points, and a leveling survey to determine the lake level elevation in January 2011.

Water depth measurements from 396 grid points and several shoreline points were collected. The secondary data were satellite images, Lake Hawassa level observation data, and the 1999 bathymetric map of Lake Hawassa. Cloud-free Landsat Thematic Mapper (TM) images (Path: 168, Row: 55) acquired on the 18 January 1985, 25 January

1999 and 10 January 2011 were downloaded from the USGS Earth explorer website (USGS, 2014). A copy of the hand-drawn bathymetric map of Lake Hawassa prepared by WWDSE in 1999 was obtained from the SNNPRS Water Bureau. The 1999 bathymetry was available only as a hard copy of four A0-size maps showing the four quadrants of the lake. Additionally, the Lake Hawassa level data was obtained from the Federal Ministry of Water, Irrigation and Electricity (MoWIE).

6.2.2 Survey and shoreline detection

A grid of points (500 × 500 m) was prepared in ArcMap 10.1 and was uploaded to the Garmin GPS. During the survey work, this grid was used to navigate the boat for depth measurement at the vertices. Echo-sounder measurements were taken in triplicate at each grid point to ensure vertical alignment of the sonar sensor and to verify consistency in measurement. The three measurements were then averaged for each grid point. Depth measurements in areas of aquatic grass and shallow depths of less than 1 m, where sounding was difficult, were made with a standard measuring rod. A leveling survey was also conducted to determine the lake level elevation from a standard benchmark located at Fikir Haik roundabout.

Lake shoreline detection from optical remote sensing has been an important method in the monitoring of lake surface extent (Dellepiane *et al.*, 2004). Lake Hawassa and Lake Cheleleka shorelines were delineated using the modified normalized difference water index (mNDWI) (Xu, 2006) analyses for images in 1985, 1999 and 2011 to derive the areal extent in their respective years. Each Landsat image was enhanced to improve the visualization, and atmospheric and sun-angle corrections were made.

The m NDWI map of Lake Hawassa for 2011 was validated using GPS readings taken during the ground survey in January 2011 to be integrated with the grid point survey data.

6.2.3 Bathymetric maps

Two bathymetric maps, namely the 1999 and 2011 bathymetric maps, were utilized to detect morphometric changes in Lake Hawassa. The 1999 four bathymetric maps were digitized in a GIS environment after being scanned and georeferenced. The contour lines were then converted to point features with elevation data as an attribute. The ArcGIS 10.1 kriging interpolation tool was used to reconstruct the 1999 bathymetry digital surface model from which the morphometric characteristics were derived.

The 2011 bathymetric map and morphometric characteristics were generated with state-of-the-art technology, using rapid surveying, portable equipment and geostatistics at low cost. Remote sensing was used for shoreline detection and ArcGIS 10.1 was employed for raster calculations, mapping and deriving the morphometric characteristics. The details are explained as follows.

6.2.3.1 Data preparation for 2011 bathymetric map

To develop a geostatistical bathymetric model for Lake Hawassa in 2011, sounding depth data were converted to elevation data by subtracting the measured depth from the lake level elevation at the grid locations resulting in point bed elevation data. The delineated and GPS verified shoreline result of the modified NDWI analysis on the 2011 Landsat image was converted to point data having the same elevation with the

Lake Hawassa level. The Lake Hawassa level elevation was determined from a standard benchmark located at the Fikir Haik roundabout by leveling survey. However, the WWDSE bathymetric map was prepared using an assumed lake water surface elevation. The water level on 21 June 1999 was taken to be 1681.7 masl (WWDSE, 2001). This datum was used to adjust elevation readings by making use of the lake level data obtained from the Ministry of Water Irrigation and Electricity. The point bed elevation data acquired from the survey in 2011 were combined with the elevation point data from the shoreline delineation to form the elevation point dataset for the geostatistical analysis.

6.2.3.2 Geostatistical analysis

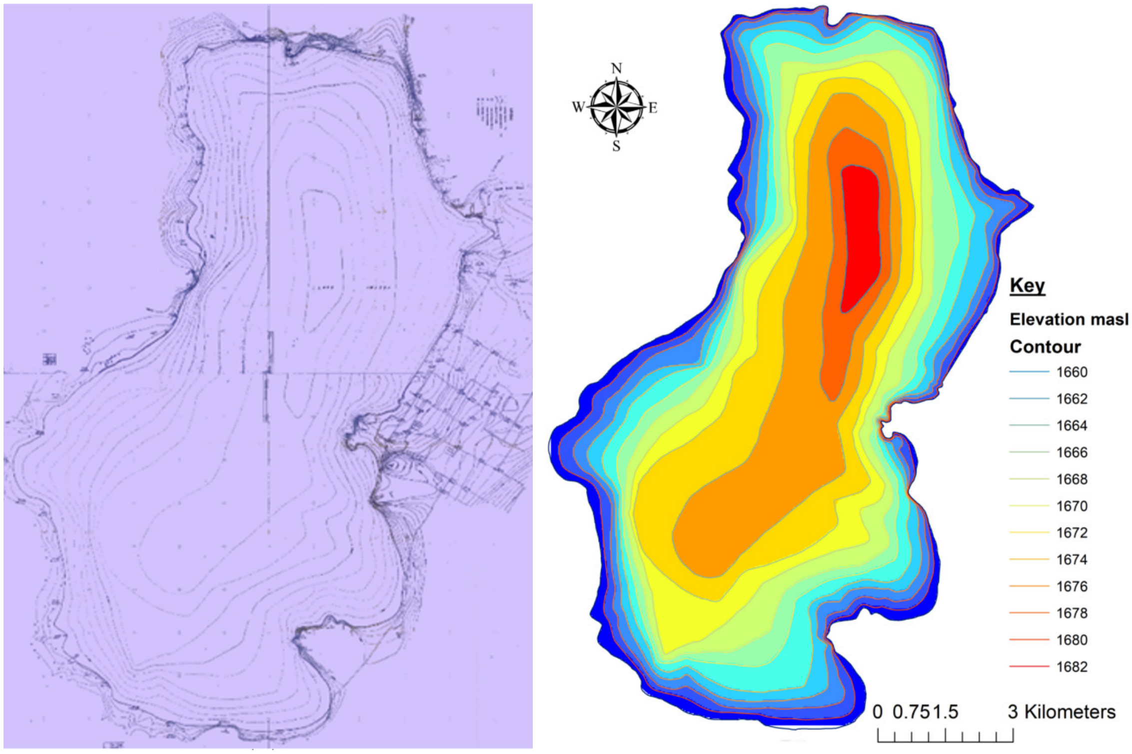
A geostatistical modeling approach known as kriging interpolation was used to predict a continuous bathymetric surface from observation points. The method is based on Tobler's premise that neighboring points are more similar than points farther away, a phenomenon known as spatial autocorrelation (Journel & Huijbregts, 1978; Trangmar *et al.*, 1986; Webster & Oliver, 2007). Spatial autocorrelation can be detected, quantified and modeled by semivariogram analysis, and used to make predictions at locations where measurements were not made (Webster & Oliver, 2007). The characteristics used to describe this semivariogram model applied for the prediction are the range, sill, and nugget parameters. Observing the plot of the semivariogram (Gamma Design Software, 2004; Webster & Oliver, 2007), the distance where the model first flattens out is known as the range where distances smaller than the range are spatially autocorrelated, whereas locations farther apart than the range are not.

The sill is the value that the semivariogram model attains at the range. The Y-axis intercept of the semivariogram plot shows the nugget effect. Kriging has the advantage that it is stochastic in contrast with deterministic techniques like trend surfaces, which predict an unknown value without an associated measure of uncertainty (Verfaillie *et al.*, 2006). Kriging indicates the errors and uncertainties associated with the interpolated values, based on a variance surface of the estimated values (Burrough & McDonnell, 1998). In this study, the kriging interpolation method was chosen over other methods for its comparatively better estimation of digital elevation model values (Davidović *et al.*, 2016).

The point dataset for geostatistical analysis were fitted to experimental semivariograms with linear, exponential, Gaussian and spherical equations. The semivariances of the different models were evaluated by calculating variances for all possible pairs of points in the dataset and assigning each pair to an interval class. The quality of the experimental semivariogram model estimated was checked by cross-validation analysis. This was a means for evaluating effective parameters for kriging interpolations by hiding information, one observation at a time. Once the variogram is selected, kriging interpolation can commence predicting the model surface. The geostatistical analysis was carried out with GS+ geostatistical software (Gamma Design Software, 2004).

6.2.4 Morphometric characterization and change detection in Lake Hawassa

Once all the maps were prepared, morphometric parameters were evaluated using ArcMap analysis tools. These parameters, defined in (Hakanson, 1981), include surface area and volume of the lake; maximum, minimum and mean length, width and depth of the lake; and hypsographic and volume curves, which determine certain elements of the lake form and also provide means to estimate the area and volume at any depth. Maps of deposition and erosion in the lake bottom were generated by differencing the 1999 and 2011 bathymetries. Multiplying the increment or decrement of bed elevation, due to deposition or erosion, by the surface area on a cell-by-cell basis, resulted in volumetric measurements of sediment change.



(a) (b)

Figure 6.1. Water Works Design and Supervision Enterprise 1999 bathymetric map. (a) Original scanned map; (b) reconstructed map

6.3 Results

During the reconstruction of the 1999 Lake Hawassa bathymetry some inconsistencies were observed on the original hand-drawn map (Figure 6.1a). The contours on the maps did not fit exactly. Therefore, necessary adjustments were made to fix the misalignment. Moreover, the island found on the northern part of Lake Hawassa was missing on the 1999 map. Comparisons were made after adjustments and correction of these errors. The reconstructed 1999 bathymetry is depicted in Figure 6.1 b.

Table 6-1. Lake area and shore length from 1973, 1985, 1987, 1999, 2011 and 2019 Landsat images.

Date	Lake Surface Area (SqKm)		Shore Length (Km)	
	Hawassa	Cheleleka	Hawassa	Cheleleka
Jan/1973	85.19	11.13	51.79	21.33
Jan/1985	90.13	7.25	54.68	42.31
Jan/1987	90.69	5.68	55.30	44.63
Jan/1999	96.85	1.34	54.61	37.28
Dec/2003	91.58	0.00	51.40	0.21
Jan/2011	93.01	0.01	57.94	0.93
Jan/2019	91.24	0.00	54.45	0.00

6.3.1 Lake Surfaces and Shore Lines

The surfaces and shorelines of Lake Hawassa and Lake Cheleleka in 1985, 1999 and 2011 were determined from the modified NDWI maps which were used to calculate the lakes' surface areas and shore lengths (see Figure 6.2). The surface area of Lake Hawassa increased by 7.5% and 3.2%, while Lake Cheleleka decreased by 87% and 99.8% in 1999 and 2011 from that of 1985, respectively (see Figure 6.3 a). According to the lake level data, Lake Hawassa registered the highest level in its recorded history in December 1998. The surface area of Lake Hawassa, therefore, must have shown an increasing trend until 1998 and a decreasing trend thereafter. The shore length of Lake

Hawassa increased over time, while Lake Cheleleka showed a decrease in shore length. Early in this century, Lake Cheleleka completely dried up.

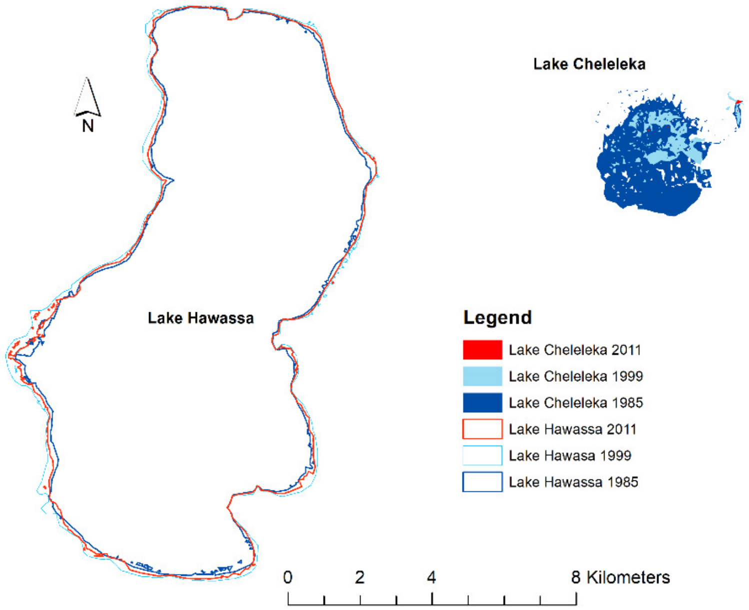
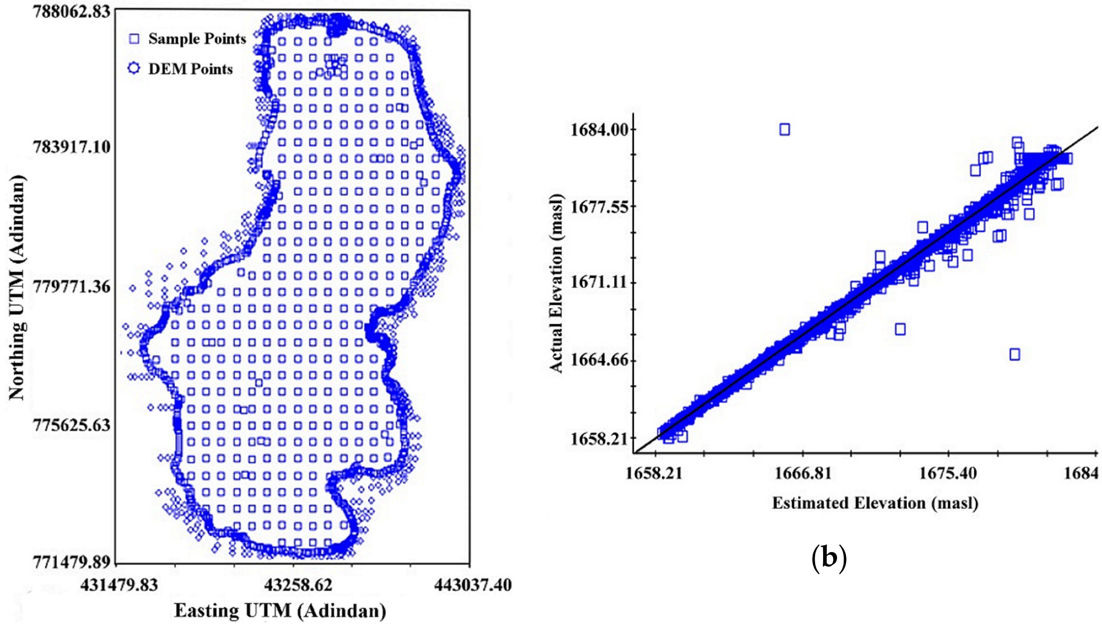


Figure 6.2. Normalized difference water index (NDWI) shoreline detection map

The LULC investigation lake surface area and shoreline length data blends well with the NDWI results. Lake Hawassa surface area was inversely proportional with Lake Cheleleka surface area till it disappears. After the extinction of Lake Cheleleka, Lake Hawassa's area starts to diminish. The increase in shoreline length in Lake Cheleleka signifies the level of fragmentation in the lake body.

6.3.2 Geostatistical analysis and bathymetry

Combined dataset from mNDWI analysis, GPS and survey point bed elevation data (Figure 6.3 a) was fitted to linear, spherical, exponential and Gaussian experimental variogram models. The spherical model was the best fit, defining the spatial structure of the variations. It had a parametric nugget value of 0.01 m2, sill value of 63.64 m2 and range parameter of 5940 m with a residual sum of squares (RSS) of 7039 and R2 0.962. The spatial dependence investigation showed an anisotropic behavior caused by the shape of the lake (i.e., the lake has greater stretch than width) which suggested the anisotropic kriging interpolation method.



(**b**)

(**a**)

Figure 6.3. Spatial dataset. (a) Grid of sampling points; (b) cross-validation analysis graph

A 10 m resolution hydrographic map of Lake Hawassa (see Figure 6.4) was developed by the kriging interpolation method. The cross-validation analysis (see Figure 6.3 b) indicated a very good fit (with standard error (SE) of 0.003, regression coefficient of 1.004, Y-intercept of −6.99 and R^2 of 0.987). Examination of the 2011 bathymetric surface model effectively represented interesting characteristics of Lake Hawassa such as the small island in the northern part of the Lake. Vertical profiles of the lake along cross-sections 1-1 and 2-2, both passing through the island, are shown in Figure 6.5.

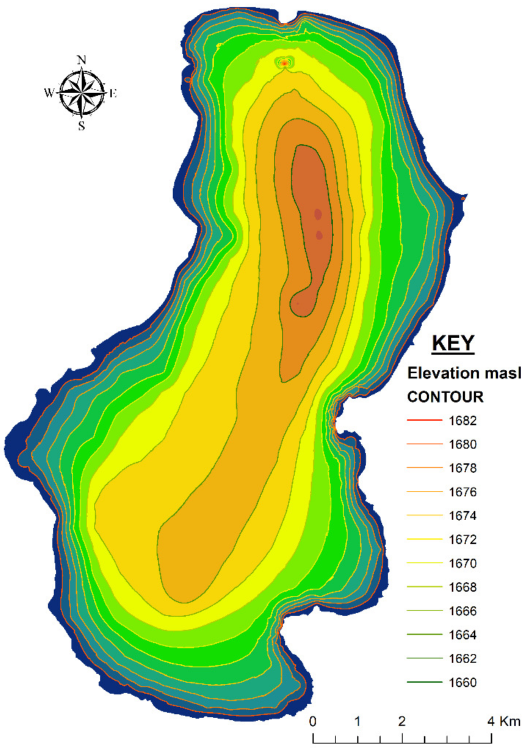


Figure 6.4. Bathymetric map of Lake Hawassa (January 2011).

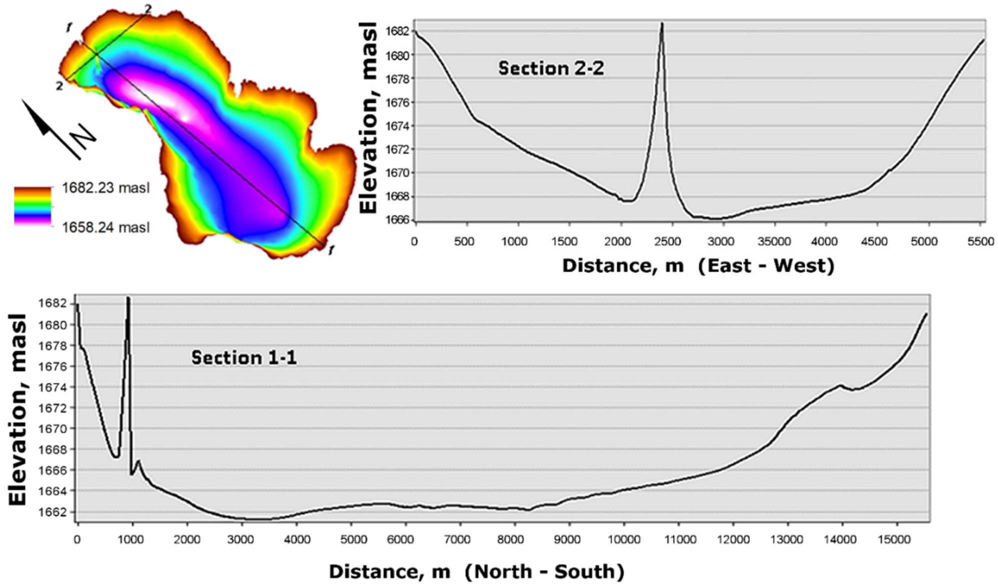


Figure 6.5. Vertical cross-section and 3D representation of Lake Hawassa.

6.3.3 Morphometric characteristics of Lake Hawassa

Physical parameters of the lake, including depth, volume, area, width and length were derived from the newly constructed bathymetry of 2011 and the reconstructed 1999 bathymetric map (see Table 6-2). As in the NDWI result in 1985, 1999 and 2011, Lake Hawassa's surface area in the 1999 bathymetric map had decreased in 2011. With the decrease in surface area in 2011, the maximum length, maximum width and mean width of Lake Hawassa decreased from that of 1999 by 110, 470 and 224.48 m, respectively. Conversely, an increase of 3990 m shoreline was observed. Within these years, the volume of Lake Hawassa decreased by about 17%. The volume change percentage was four times more than that of the surface area change. This has resulted in the reduction of the mean depth by 1.86m and lake level by 0.87 m during the same period. The minimum bathymetric elevation remained more or less the same.

Table 6-2. Morphometric characteristics of Lake Hawassa

Period	Elevation (masl)	Area (km²)	Volume (MCM)	Length L Max (km)	Width W Max (km)	Width Mean (km)	Shore Line SL (km)	Depth Mean (m)	Depth Max D (m)	Relative Depth Dr (m)
1973 †	1679.79	92	1152.16	15.75	8.75	5.841	46.75	12.52	21.09	0.195
1999 †	1681.92	100	1356.12	17.12	9.51	5.841	52.84	13.56	23.22	0.206
1999 ††	1681.92	97.25	1174.61	16.05	9.02	6.059	50.69	12.08	23.22	0.209
2011	1681.05	93.01	1123.87	15.94	8.55	5.835	54.68	12.08	23.34	0.215

The relative hypsographic curves (see Figure 6.6) show that Lake Hawassa has a concave upper portion and convex lower portion. This may be attributed to sediment movement within the Lake bed. It was also evident from the comparison of the hypsographic curves that in 2011 there was a horizontal cross-sectional area increase in the top 18–50% cumulative depth and a decrease in the bottom 65–88 cumulative depth percentage. Relative cumulative volume curves (see Figure 6.7) depicted volume increase in the top 30% and a decrease between 50–75% of the cumulative depth. The increase in area and volume (as shown by the relative hypsographic and volume graphs) could be explained by the erosion of sides of the walls of the lake bed while the decrease is attributed to the deposition of sediments. The flat shapes of both curves suggest that small depth variation near the top surface results in considerable variation in the volume and surface area of the lake. The magnitudes of the slopes of the curves also suggest that small volumetric increases result in large surface area coverage. This explains the increase in surface area and, thereby, the increase in the perimeter, maximum length and width of Lake Hawassa in 2011.

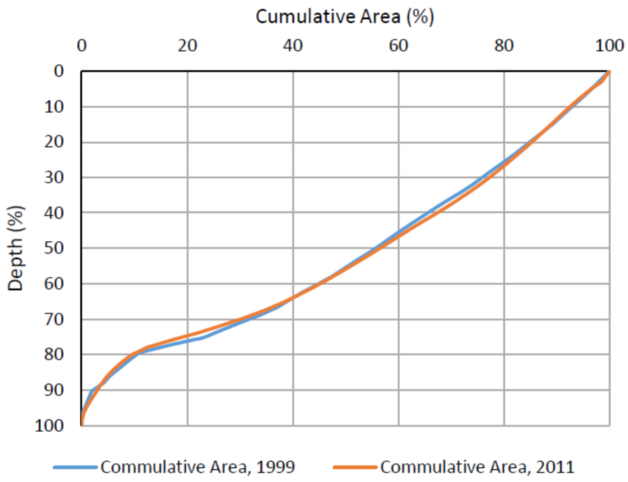


Figure 6.6. Lake Hawassa relative hypsographic curves.

The spatial comparison by differencing the 2011 and 1999 bathymetries depicted that much of the western and eastern part of the Lake and north-eastern shores had sediment build up (see Figure 6.8). The north-western, south-eastern as well as some central pocket parts of the lake were eroded. This comparison took into account the volume implication due to the island on the 2011 bathymetry. About 77.86 million cubic meters of silt was deposited over the 49 km2 area of the bottom surface. The additional capacity of 31.2 million cubic meters was created by erosion (sediment movement) of the lake bed. Siltation has cut about 46.66 million cubic meters of the lake's volume, which was about 4% of the volume in 2011. Although deposition was observed over a vast surface of the lake, the northern and southern parts of the lake each accounted for about 11% of the deposition. About 47% of the deposition occurred in the western part, while the remaining 30% was deposited adjacent to Hawassa Town.

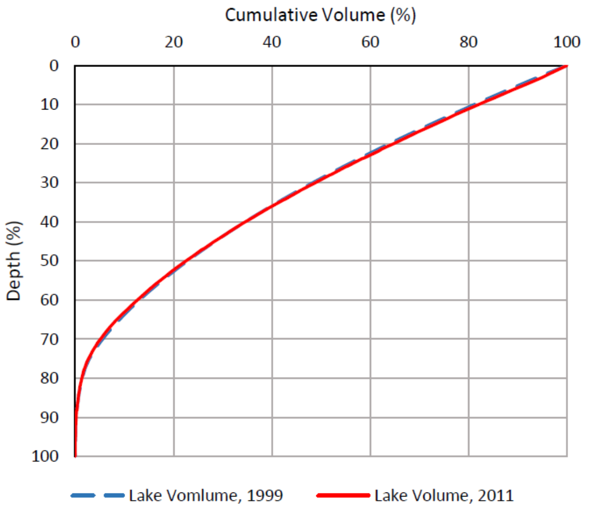


Figure 6.7. Lake Hawassa relative volume curve.

6.4 Discussion

The mNDWI analysis for the images of 1985, 1999 and 2011 showed that Lake Hawassa coverage had an increasing trend up to the late 1990s and a decreasing trend afterwards, while the surface area of Lake Cheleleka decreased to the point of disappearance. Lake Cheleleka lost 5.9 km^2 of its surface between the years 1985 and 1999 at a loss rate of 0.422 km^2 loss per year. If this rate persisted, the lake would disappear in about four years after 1999. In fact, inspection of Landsat images from 2000–2003 showed the lake completely dried up in the dry season of 2002 indicating the actual rate was even faster. Nonetheless, small inundations still collect sporadically during wet seasons. Between the years 1973 and 1999, Lake Hawassa's surface area increased by 8.8%, its depth rose by more than 2 m and its volume increased by 17.7% (WWDSE, 2001). Most of these changes were observed in the latter years. For instance, substantial surface area increase (7.5%) occurred between 1985 and 1999. Since groundwater levels were influenced by the water levels of the surrounding water bodies 14,15, the increase may also be linked with the significant surface area decrease (87%) in Lake Cheleleka during the same period. In 2011, however, Lake Hawassa seemed to have attained a new equilibrium with lesser surface coverage (3.2%) than in 1985. Regarding the volume of Lake Hawassa, about the same percentages of volume, 17.7% and 17%, were lost between the years 1973–1999 and 1999–2011 respectively. Although the percentages were similar, the rate of volume loss more than doubled between the two time periods.

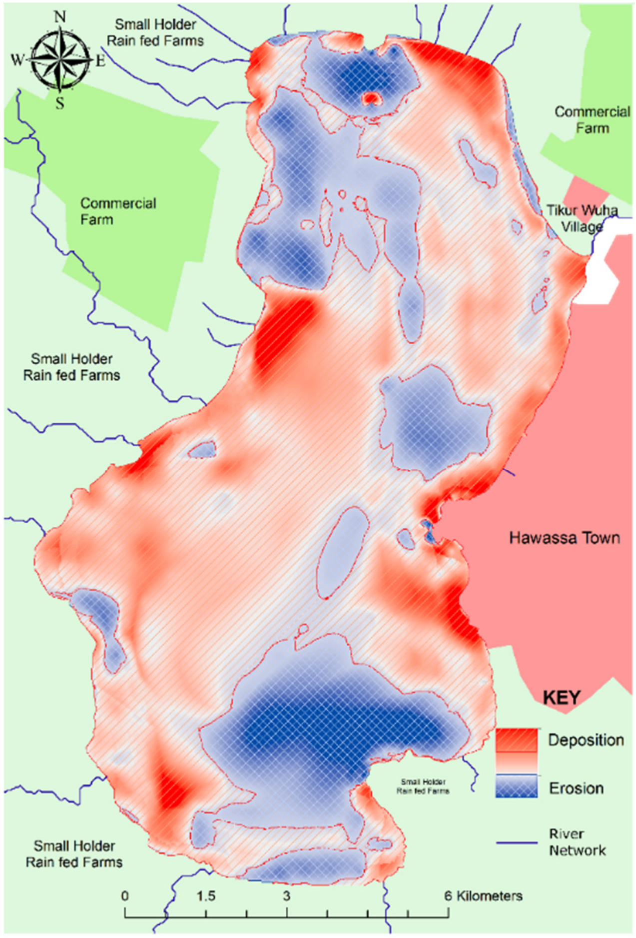


Figure 6.8. Lake Hawassa erosion and sediment deposition areas

This study exemplified the importance of bathymetric investigation in that an increase in surface area and lake level may not necessarily increase lake volume. Monitoring the surface of a lake alone may lead to inaccurate conclusions about the state of a lake. The information derived from the bathymetric investigations has also showed morphometric changes that resulted in volumetric changes of Lake Hawassa during 1999–2011. The changes in morphometry of Lake Hawassa seen in the relative hypsographic and volume curves were also evidently varying with depth. The increase in cross-sectional area at relatively shallow depths (18–50%) could be explained by the erosion of the lake bed with high elevation, while the decreased area at deeper levels (65–88%) was attributed to the deposition of sediments. Correspondingly, the increase in volume in the top 30% and decrease in volume at deeper depths as depicted by the relative volume curves may likewise be attributed to the erosion and deposition of sediments. Although there was erosion and deposition at different parts of the lake bed, Lake Hawassa has lost 50.74 million cubic meters of volume to sedimentation. Siltation to the lake due to land-use change in the catchment has been reported (Ayenew & Tilahun, 2008). The overall 4% volumetric decrease in just one decade signifies the importance of catchment management in the watershed.

Three deposition zones, namely the western, northern and eastern, were identified in this study. The northern and eastern zones were dominantly areas of shore development for residential purposes. The town of Hawassa is located on the eastern shore (Figure 9). Reduction in depth in these parts of the lake could be attributed to urban development. The fact that the town's road network is aligned with the slope of the watershed would easily transport sediment materials via the drainage canals that end up in the lake. The western zone is largely agricultural land where small farms and medium commercial farms are located up the slope. These farms have sparse vegetation cover and are left fallow in the dry season, as they are mainly rain fed, favoring erosion during the rainy season.

During the period 1965 to 1998 agricultural land and urban areas increased from 28.41% to 41.96% and 0.34% to 1.23%, respectively, while the natural vegetation decreased from 47.03% to 37.98% (Shewangizaw, 2010). Natural land-use types such as water body, swamps, grassland and shrub land also decreased in the same period. Land-use assessment for the time span 1973 to 2000 also showed similar trends in urban area development and agriculture expansion, and reduction of the woodlands, water body, grassland and swamps (Abraha, 2007). In 2011, agricultural land, the dominant land-cover type in the watershed, had increased to 56.4% (Wondrade *et al.*, 2014). The anthropogenic (i.e., urban and farm development) factors probably were directly linked to the spatial sediment distribution on the lake bed impacting the morphometry.

However, streamflow, the transporting agent of the silt, may not only be influenced by human activities. Makin et al. (Makin *et al.*, 1975) reported that in the 1970s surface flow from the northern and western parts of the catchment occasionally reach the lake and runoff contribution was mainly from Tikur Wuha River. Nowadays, huge gullies have emerged especially on the western part of the lake watershed where farming is the dominant activity and where land cracks were recently reported. The importance of tectonic activities in changing the hydrodynamics of the lake, as indicated in

(Ayenew & Becht, 2007), may also have resulted in the silting up of the lake. Therefore, the impact of tectonic activities should be studied further.

To mitigate the siltation problem, resulting from the LULC changes, appropriate soil and water conservation measures are vital. Best-management practices of minimum tillage, biological and mechanical soil conservation measures, and cover cropping could be applicable to the agricultural areas while the urban sediment issue can be addressed by the proper control of urban development (construction of infrastructures and houses), constructing water and sediment control ponds and stilling basins, especially at the inlets. In light of the spatial distribution of the sediments in the lake bed, watershed management in the catchment requires a thorough investigation.

The 2011 bathymetric and sediment maps can be used in various limnologic, hydrologic and watershed management studies, environmental impact assessment studies, and navigation. The maps also further the spatial database of Lake Hawassa besides proving the goestatistical approach of developing lake bathymetries to be quick and cost effective.

6.5 Conclusions

The spatial extent of water bodies in the Hawassa watershed and morphometric changes in the lake were investigated in this study. A hydrographic map of Lake Hawassa was prepared from gridded sounding data, GPS data and satellite images using a geostatistical method. The bathymetric surface generated by kriging was utilized to extract information about the lake's characteristics. The 10 m resolution hydrographic map accurately depicted the features of the lake. Morphometric characteristics of the lake in 2011 were compared with the bathymetric map prepared in 1999 by WWDSE. The latter was reconstructed from the only available four A0-size hand-drawn maps.

The study revealed that there had been morphometric dynamics in Lake Hawassa and the adjoining Lake Cheleleka as a result of natural and anthropogenic activities between the years 1999 and 2011. The surface area of Lake Hawassa increased and later declined while Lake Cheleleka declined to the point of disappearance. Lake Hawassa's volume and lake level followed a similar trend to the surface area variation. However, the rate of change of lake surface area and volume were not straightforward. Generally, although there was increase in surface area and lake level, the lake volume decreased during the study period. This evidences the importance of bathymetric investigation. Monitoring the surface of a lake alone may lead to inaccurate conclusions about the state of a lake.

In Lake Hawassa, three siltation zones were identified: the northern, eastern and western parts of the lake bed representing their respective parts of the lake watershed. These zones were most probably linked with the anthropogenic factors of farming and urban development contributing to the lake's morphometric dynamics. These zones should be focus areas for timely interventions on catchment rehabilitation and proper land and water management practice to minimize or avert the anthropogenic influences.

The changes, however, may not have been solely due to these anthropogenic factors. Tectonic activities may also have potential impacts on the hydrology of the lake which will aggravate the problem. The study demonstrated the use of geostatistical modeling as a timely and cost-effective bathymetric mapping approach.

CHAPTER 7: ASSESSING THE IMPACTS OF LAND USE CHANGES ON TIKUR WUHA CATCHMENT HYDROLOGY USING MIKE SHE

7.1 Introduction

Knowledge of the continuous movement of water between the atmosphere and the earth, both above and below the surface, and each component of the hydrological cycle as well as the interactions amongst the different components of the cycle is fundamental to the management, development and monitoring of water resources (Fan & Shibata, 2015; Tomer & Schilling, 2009). Hydrological models have been used to analyze, understand, and explore solutions for sustainable resources management. In areas where complex hydrological regime exist, a comprehensive physically based method considering surface-water-geology framework is required to better represent the interaction between groundwater and surface water, and substantiate these interactions in relation to climate, land forms (LULC), geology and biotic factors (Sophocleous, 2002; Wijesekara *et al.*, 2012). Modeling surface water and groundwater interaction, impacted by LULC changes, has been an important research topic in the field of hydrology in recent times (Mohammed, 2009). However, most of the hydrological models used to study LULC change impacts focus on either surface or groundwater system by simplistic representation of one of the systems when modeling the other. In hydrological systems such as the Ethiopian Rift Valley Lakes region, where lakes are the central elements, the lakes responses are mainly controlled by the processes and their interactions in their catchments (Vallet-Coulomb *et al.*, 2001).

Impacts of climate variability vary considerably as a result of contrasting change signals such as increase or decrease in annual precipitation and temperatures aided by, more regional characteristics, such as orography and distance to the coast, that affect how the large-scale changes in climate emerge locally (van Roosmalen et al., 2009). Climate variability impacts are also aggravated by dominant hydrological processes. In an area where surface runoff is the dominant process, increase in precipitation events can have a considerable impact than groundwater-fed systems (Christensen & Christensen, 2004). For systems where lakes are the pivotal parts of the environment, like in that case of Hawassa watershed, climate variability affects the surface and groundwater systems differently. However, the majority of hydrological climate change impact studies focus mainly, as well, on surface water such as rainfall-runoff processes (van Roosmalen *et al.*, 2009). And so, examining the hydrological fluxes for LULC impacts in watersheds such as Lake Hawassa entails the consideration of the entire surface and groundwater system. In this study MIKE SHE, a coupled surface and groundwater modeling system was used to investigate the responses of Hawassa watershed (Tikur Wuha catchment) to LULC changes and climate variability.

7.2 Modeling Endorheic Hawassa Watershed

Extensive alterations in LULC, which in turn impact the hydrological system at different scales, have occurred throughout Africa for the last more than 50 years (Li *et al.*, 2007). These impacts were manifested in altering the balance between rainfall, ET, percolation to the unsaturated and saturated zones, and the resultant streamflow.

Physically based and spatially distributed hydrological models are increasingly used to address the hydrological impacts for understanding or predicting the potential hydrological consequences apart from after-the-fact analyses thereof.

Lake Hawassa basin is a closed basin with an open groundwater system. Very little is known about the surface-groundwater interactions to explain the changes in the watershed. The hydrogeological setup of the area are volcanic origin consisting volcanic strata and sediments (Tilahun, 2006). This setup is moreover sectioned by faults which facilitate the interconnection between the closed surface and open groundwater systems. In the past, there have been attempts to quantify the surface and ground water resources of the Hawassa watershed. However, these attempts were not adequate mainly because they were partial (they considered either surface or groundwater only) and there were huge variations on estimates of the components.

In this study a coupled surface and groundwater modeling system , MIKE SHE, fit for modeling wetland situations (J. Thompson *et al.*, 2004), was used to characterize the responses of Hawassa watershed to LULC changes and climate variability. A key benefit of using MIKE SHE is that it simulates all the processes in the hydrological cycle by fully integrating the surface, subsurface and groundwater flow with limited data. Moreover, simplified models can be developed initially and then made more complex later as additional information is made available (Prucha *et al.*, 2016). Therefore, MIKE SHE hydrologic models were developed for Tikur Wuha River catchment with the aim of assessing the impact of LULC change in Hawassa watershed.

7.3 Materials and Methods

The following sections will describe the methodology followed in this investigation.

7.3.1 Model description

MIKE SHE is a deterministic, fully-distributed and physically-based hydrological and water quality modeling system (DHI, 2017). The Water Movement module has been designed with a modular structure in which six process-oriented components of the land phase of the hydrological cycle such as ET, interception, overland and channel flow, unsaturated flow and groundwater flow including river-aquifer interactions (Figure 7.1). The modules are based on physical laws which are derived from forms of the laws of conservation of mass, momentum, and energy.

The actual ET is calculated using the Kristensen and Jensen methods (Kristensen & Jensen, 1975) based on reference ET, leaf area index (LAI), root depth (RD) for each vegetation type, and a set of empirical parameters. Input reference ET can be calculated in numerous ways. In this study, FAO-penman method of computing reference ET was used. Channel flow is handled using one dimensional (1-D) diffusive wave Saint Venant equations and overland flow is calculated using two dimensional (2-D) diffusive wave Saint Venant equations. Water infiltrating into the unsaturated zone (USZ) can be modeled using the 1-D Richards flow or gravity flow. The saturated zone is modeled using a three dimensional (3D) Boussinesq equation (Boussinesq, 1904) which uses finite difference methods to solve the partial differential equations. Some aspects of MIKE SHE are empirically based (DHI, 2004).

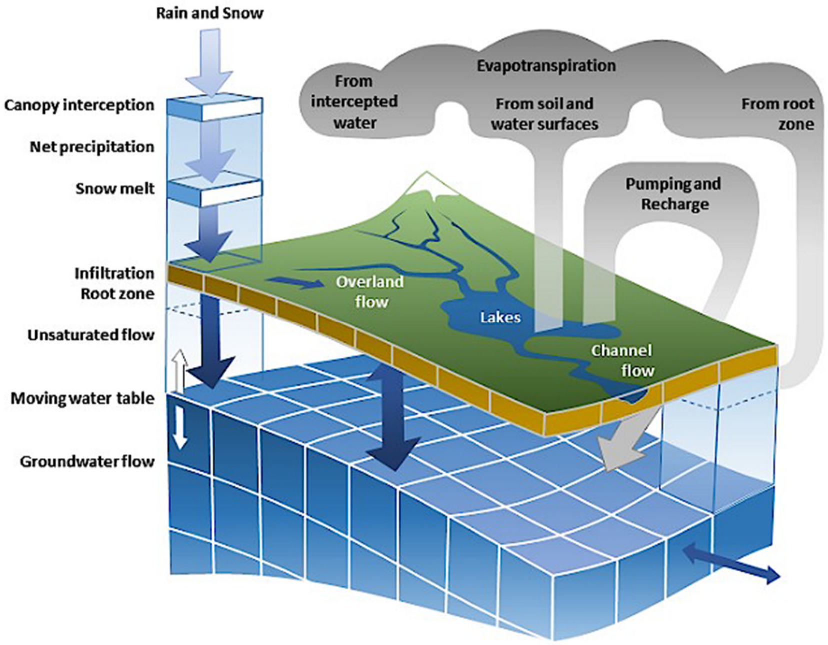


Figure 7.1. Three dimensional schematic representation of the MIKE SHE model

7.3.2 Model setup and parameterization

MIKE SHE/MIKE 11 models were setup for the only gaged stream, Tikur Wuha, in Hawassa watershed. Table 7-1 shows dataset types, descriptions and processing for the MIKE SHE model set up. There are two gaging stations in the catchment located at the Tikur Wuha Bridge and Dato village. Tikur Wuha Bridge was established and had been recording data since mid-1972 and Dato village station was constructed in 1980 to mitigate the backwater effect by Lake Hawassa during rainy seasons. Although both stations were recording Tikur Wuha flow, the author observed that there are serious problems as to how the data measurements were taken. Due to the difference on the flow amount recorded in these stations, two models were setup, calibrated and validated based on the flow measured at these stations. The period from 1980 to 2002 is a period for which there exists recorded streamflow from the two stations. Therefore, this period was used to compare the models' outputs.

Table 7-1. Dataset descriptions and preparation

Data type	Description of data and processing
Manning number M	Uniform value for the Manning's M roughness coefficient was assumed initially and later was used as a calibration parameter.
Soil structure	Soil types and properties were derived from the Rift valley master plan study document prepared by the then Ministry of Water. Different saturated hydraulic conductivity (Ks) values were assigned based on geology of the formations but later appropriate values were assigned to horizontal and vertical hydraulic conductivities during the calibration.
Groundwater table	Initial potential head (IPH) was assumed to be 2 m below the ground configuration. Although IPH was assumed initially, it was extracted from the best simulation model, to be used as model adjustment variable.
Hydroclimate data	Climate data (rainfall, temperature, precipitation, wind speed, sunshine hours and relative humidity) were acquired from NMA measured at stations within and nearby the watershed namely Hawassa, Haisawita, Yirba, Wondo Genet and Shashemene whenever available. Flow data at the two stations were accessed from the Ministry Of Water Irrigation and Energy.
Topography	A DEM (SRTM 30m by 30m resolution) was obtained from USGS and hydrologically corrected using ArcHydro hydro-processing tool in ArcGIS.
Cross sections of the river network	The river network comprised 20 branches following the main Tikur Wuha River. The branches were generated from the DEM. A total of 94 cross sections were used to represent the whole river network. It is assumed that the digitized cross sections from the hydrologically corrected DEM adequately represent the river bathymetry for this study.
Measured discharge	Tikur Wuha bridge and Dato discharge measurement data were obtained from the Ministry of Water Irrigation and Energy.

7.3.2.1 Watershed discretization

Model shape file inputs such as river network, watershed boundary and river cross-sections were generated from a 30m by 30m resolution SRTM DEM. A courser grid of 200 X 200 m was later used in the model to run the simulations.

7.3.2.2 Meteorological data

Rainfall records were acquired from four nearby stations managed by the National Meteorology Agency. Spatially distributed rainfall for the watershed was generated by using Thiessen polygon method. Rainfall data were used as an input in each grid on a daily basis for model set-up. Reference ET was calculated using the method of FAO Penman–Monteith (Allen *et al.*, 1998) for Hawassa station and due to limitation of meteorological data for the rest of the stations temperature based evapotranspiration was estimated using FAO ETo calculator (Raes & Munoz, 2012).

7.3.2.3 Land use and land cover data

Vegetation specific parameters for the model were derived from data of 1973, 1987, and 2003 LULC maps. These maps were selected based on the result of hydrometeorological data analysis where changes in regimes were observed. The catchment is characterized by a high percentage of cultivated land on the hill tops and grassland and lakes in the valley. Detailed comparisons of the maps show that land use changes are unevenly distributed within the watershed. Consequently, LULC data of 1973 was used for the model calibration and validation, and change analysis was done based on 1987 and 2003 LULC maps.

Time series for leaf area index and RD for the simulation periods were generated to estimate transpiration from the vegetation in the different LULC classes. Because there were no field data available for each LULC types, this study utilized published and unpublished reports and journal articles to obtain most of the vegetation specific parameters. A value of 0.01 for RD and 0.01 for LAI were used to lower ET in built up areas.

7.3.2.4 Unsaturated and saturated zone

While two layer unsaturated flow model was selected for the unsaturated zone, a uniform 200 m deep saturated layer was considered for the saturated zone. Secondary data from basin master plan studies and data from Water Bureau of the SNNP Regional State were used to generate parameters for saturated and unsaturated zones (soil water content at saturation, field capacity and wilting point).

Although the watershed had detailed soil types reported in literature, in this study only the major soil types and their parameters were considered in the modeling. Saturated soil hydraulic conductivity (Ks) values for the major soil types were estimated from published literature in the study area (Tilahun, 2006) in addition to the secondary data collected from the regional water bureau. During the simulation, the model estimates the water content of unsaturated soil from the water retention and unsaturated hydraulic conductivity functions. The Van Genuchten (Van Genuchten,

1980) model was fitted to describe retention curve and hydraulic conductivity. The parameters were estimated using the percentage clay, silt and sand as given by the secondary input data.

7.3.2.5 Overland flow and channel flow

The overland flow module requires Manning number (M), detention storage and initial water depth to generate flow. A uniform Manning number, 20 $m^{1/3}/s$, was used to set up the model but was later it was used as an auto-calibration parameter because surface flow dominates the stream flow. Uniform values of 8.6 mm and 0 mm were used for detention storage and initial water depth in the model. Drainage network consisting of 20 channels were extracted from a DEM processing analysis. Channel leakage coefficient was set as 1e-006/s as recommended on the MIKE SHE manual. Ninety four cross-sections were defined at the initiation at the middle and at joining points and additional cross-sections were also added for longer river reaches as required. Dynamically coupled to MIKE SHE and a fully unsteady river hydraulic model, MIKE 11, ware used to simulate river flow and water level in all reaches of the river network.

7.3.2.6 Simulation time steps

MIKE SHE has the flexibility of using variable simulation time steps in modeling different hydrologic components and flow characteristics. A 24 hour time step was used in the simulations.

7.3.2.7 Default parameters

Various default parameter values of the models were used as set in the model and recommended in the manual and reference documents of the MIKE SHE model.

7.3.2.8 Model performance evaluation methods

The model performance was generally evaluated by visual inspection of the simulated versus observed discharge hydrographs in addition to the six quantitative statistics namely Mean Error (ME), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Standard Deviation of the Residuals (STDres), Correlation Coefficient (R) and Nash Sutcliffe Correlation Coefficient (R2).

7.3.3 Model calibration and validation

At the initial stage of calibration, ‘’trial and error’’ procedure was applied to examine the influence of various model parameters by checking the evaluation statistics. Initial values and, minimum and maximum value ranges of 26 parameters were assessed from field data (secondary sources) and general characteristics of the parameters prior to calibration. Calibration in MIKE SHE can be performed either manually using a trial and error method on parameters or by employing the automatic calibration tool for parameter optimization, sensitivity analysis or scenario management (DHI, 2017).

7.3.4 Running the model

The MIKE SHE models were initially run from 1970 to 1978 on a nine year time period for the Bridge model and from 1978 to 1984 for the Dato model. A warm up simulation period of three years were used to integrate natural values of the saturated zone and lower level hydrology parameters where default values were utilized for both models. This ensured that the initial values at the start of the testing period to be more representative of the conditions in the watershed at that time. The models were calibrated and evaluated against streamflow data collected at the middle (Dato village) and at the outlet (Tikur Wuha Bridge) of the watershed. The intervals of the calibration and validation periods were chosen on the basis of the results of trend analysis of the climate variables. Accordingly, the calibration data ranged from January 1973 to December 1978 while validation data ranged from January 1979 to December 1987 for Bridge model while calibration data ranged from January 1980 to December 1984 while validation data ranged from January 1985 to December 1987 for Dato model. Most sensitive parameters available for calibration and a possible range of each parameter are detailed in Table 7-2.

Simulation and calibration of the models took several days on a workstation with 32 processors, operating at a clock speed of 2.6 GHz. However, it was not possible to reach convergence due to power interruptions. As a result, it was necessary to switch onto a laptop computer with four processors operating at a clock speed of 2.50 GHz which took more than 8 hours to simulate and more than two weeks to calibrate the model. This process took several months to get the model in the acceptable accuracy range.

Initial depth of the phreatic groundwater table of the unconfined aquifer was extracted after the simulations and continually updated until satisfactory results were attained. Twenty six parameters were used in the auto-calibration process including Manning's number, detention storage coefficient and the six geological units' saturated hydraulic conductivities (horizontal and vertical) and specific storage and specific yield (horizontal and vertical) considered in the modeling.

7.3.5 Climate variability impacts

Climate variability impacts were assessed by keeping LULC and other none climate variables constant in the second homogeneous period (1988 - 2002) and compare it with the first period (1973 – 1987). This showed the impact on the hydrological fluxes and their response on the water balance of the watershed. To see the variability with respect to LULC the three LULC maps were used.

7.3.6 Land use land cover change impacts

Land use change impacts were assessed by partitioning the hydrometeorological time series based on their homogeneity periods and comparing the simulated hydrologic fluxes in the two periods (1973-1987 and 1988-2002). Likewise, simulated streamflow was compared with the observed Tikur Wuha River flow. Moreover, the impact assessment also looked into the water balance of the different hydrologic components during these periods and comparing the two models results from the three LULCs. The models provide as outputs the water balance in daily, monthly and annual time steps as well as output maps or time series for all water balance components. The models simulated all hydrological processes including ET, runoff and storage changes on the surface, unsaturated and saturated zones.

7.4 Results and Discussion

The quality of input data, estimated or measured parameters to the models and the quality of the daily measured discharge data against which the simulated flow is compared are crucial for the calibration exercise in order to obtain good performance. Despite data scarcity and quality, the models produced very good simulation results at the daily time steps with parameters calibrated and validated against measured discharge data at the two stations.

Table 7-2. The most sensitive 10 parameters of the 26 calibration parameters used for autocalibration

Parameter	Initial Value	Lower Bound	Upper Bound
Specific Storage for Geologic Unit 4 (Ss4)	4.5E-03	1.0E-04	5.0E-03
Horizontal Ks* for Geologic Unit 5 (Kh5)	1.2E-03	5.8E-04	1.7E-03
Specific Storage for Geologic Unit 1 (Ss1)	6.6E-04	1.0E-04	5.0E-03
Horizontal Ks for Geologic Unit 4 (Kh4)	4.8E-04	1.2E-04	8.7E-04
Vertical Ks for Geologic Unit 4 (Kv4)	1.9E-04	1.2E-04	8.7E-04
Horizontal Ks for Geologic Unit 2 (Kh2)	1.1E-04	1.2E-05	1.2E-04
Horizontal Ks for Geologic Unit 6 (Kh6)	5.8E-05	1.2E-06	5.8E-05
Horizontal Ks for Geologic Unit 1 (Kh1)	5.8E-05	1.2E-06	5.8E-05
Vertical Ks for Geologic Unit 1 (Kv1)	4.3E-05	1.2E-06	5.8E-05
Horizontal Ks for Geologic Unit 3 (Kh3)	3.6E-05	1.2E-06	5.8E-05

Ks* Saturated hydraulic Conductivity

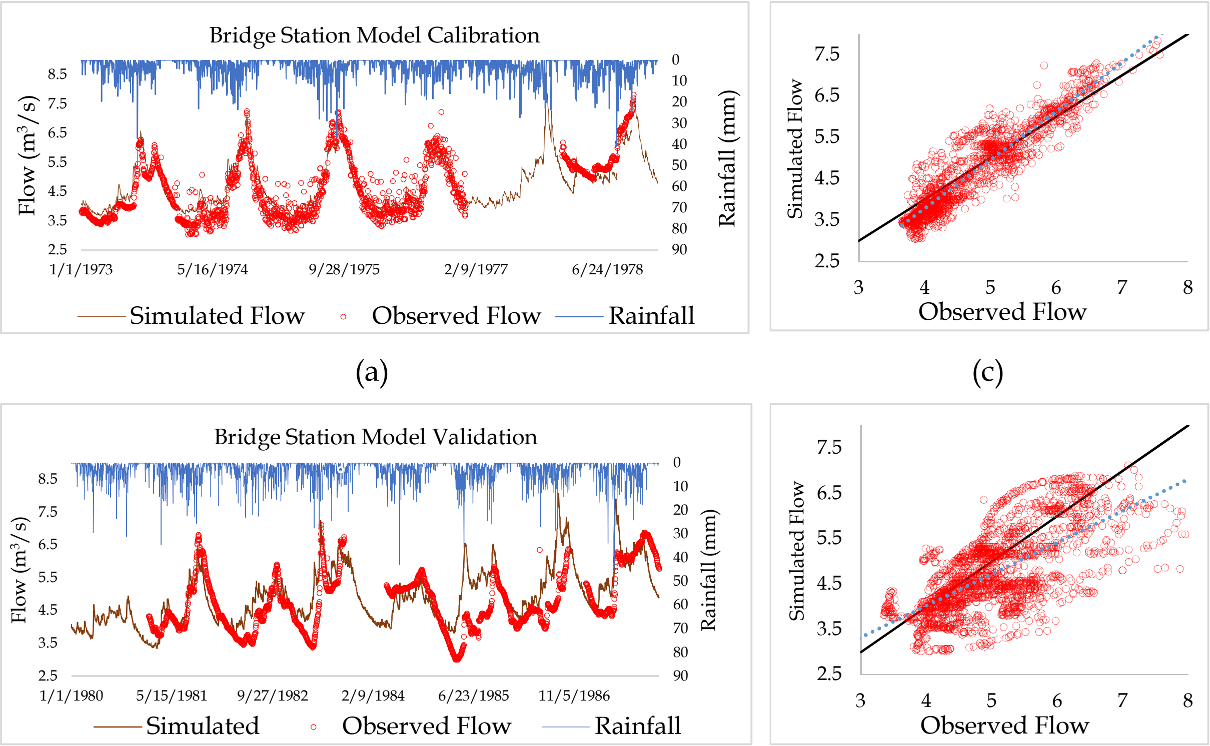
Sensitivity analysis suggested that out of the 26 calibration parameters ten were very sensitive (see Table 7-2). Satisfactory resemblance was achieved between the observed and simulated daily streamflow for both bridge and Dato village models.

For the calibration period, the correlation coefficient and model efficiency for daily streamflow values were 0.93 and 0.84 at Tikur Wuha Bridge model respectively. According to the performance criteria (Henriksen *et al.*, 2003), this result can be considered ‘‘very good’’. These values for the validation period were 0.77 and 0.57, respectively which are considered “good” likewise. The correlation coefficient and model efficiency for daily streamflow values for the calibration and validation periods at Dato model were also “good” according to the same criteria. Computed model performance evaluation parameter values during the calibration and validation period are presented in Table 7-3.

Table 7-3. Calibration and Validation statistics of the Bridge and Dato models

	Tikur Wuha Bridge Model			Dato Village Model		
Model run	Overall	Calibration	Validation	Over all	Calibration	Validation
Simulation period	1973-87	1973-78	1979-84	1980-87	1980-84	1985-87
ME	0.058	0.036	0.098	-0.265	-0.141	-0.459
MAE	0.438	0.326	0.427	0.626	0.563	0.725
RMSE	0.559	0.410	0.536	0.720	0.674	0.786
STDres	0.556	0.409	0.526	0.669	0.659	0.639
Correlation (R)	0.80	0.93	0.77	0.83	0.85	0.85
Nash Sutcliffe (R2)	0.64	0.84	0.57	0.59	0.62	0.55

Mean daily simulated and observed streamflow for the calibration period were 5.55 m^3/s and 3.68 m^3/s, for Bridge and Dato models respectively, with a difference of 33.6%.

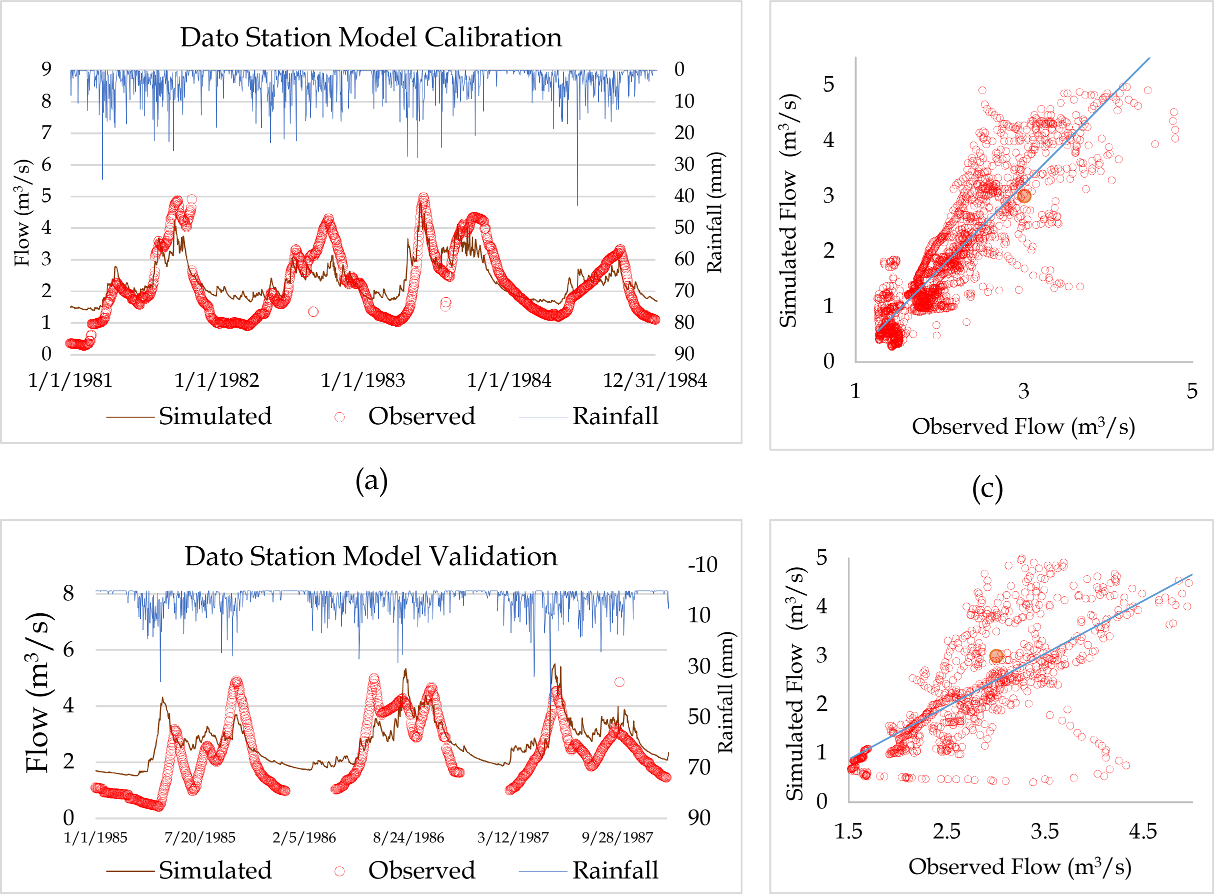


(a) (c)

(b) (d)

Figure 7.2. Tikur Wuha flow hydrographs during calibration and validation period (Bridge Model). (a) and (b) hyetograph and corresponding hydrographs of flow; (c) and (d) scatter plots of observed verses simulated flows at (a) and (b), respectivel123y

Model calibration and validation for daily flows shown that the Bridge model could capture the dominant runoff process and streamflow dynamics of the Tikur Wuha watershed (see Figure 7.2). Reasonable coefficients of Nash Sutcliffe correlation coefficient of 0.84 and 0.57 for the Bridge model and 0.62 and 0.55 for the Dato model, and overall RMSEs of 0.559 and 0.72 for model calibration and validation period were obtained despite the fact that the models both overestimated and underestimated streamflows during some parts of the simulation periods.



(a) (c)

(b) (d)

Figure 7.3. Tikur Wuha flow hydrographs during calibration and validation period (Dato Model). (a) and (b) hyetograph and corresponding hydrographs of flow; (c) and (d) scattered plots of observed verses simulated flows at (a) and (b), respectively

The models' simulated streamflows were in agreement with the observed values for the calibration and validation periods. In terms of timing and quantity, rainfall hyetograph shows a consistent correspondence with the simulated hydrograph of both stations (see Figure 7.2 and Figure 7.3). Scatter plots of observed verses simulated flow shows the closeness between the values especially on the calibration periods (see Figure 7.2 (c) and (d), and Figure 7.3 (c) and (d)).

7.4.1 Hydrological response to land use land cover changes

Land use land cover change alters the proportion of the different hydrologic processes. For instance, since forests evaporate more water than grass or cultivated crops (Zha et al., 2010) conversion of forests to cultivated land will reduce ET. Likewise, conversion of one LULC type into another is expected to result in the increased or decreased runoff. For streams feeding lakes, this may result in increased or decreased lake levels. Evapotranspiration, accounting for the highest proportion of the rainfall fraction in the watershed, and the other water balance components impacts by the LULC changes are discussed below.

7.4.1.1 Land use land cover change impacts on evapotranspiration and streamflow

The hydrological investigation results showed that a considerable portion of the rainfall is passed off through ET losses that represent approximately 84% and 87% of the total rainfall during calibration and validation periods respectively for the Bridge model. The Dato model as well rendered similar breakdown of evapotranspiration proportions (82.6%) during the calibration and validation periods.

The data span from 1981 to 2002, for which streamflow data were available for the Bridge and Dato stations, was chosen to make a comparison between the Bridge and Dato models so that insights are highlighted on the water balance components of the watershed as impacted by the LULC changes. As shown in Table 7-4 Bridge and Dato models gave in average 85.1% and 85.3% evapotranspiration and 23.7% and 20.2% river flow proportions of the total rainfall. The fact that the sum of the proportions of these variables is more than hundred percent is showing the watershed is giving off its water reserves.

Table 7-4. Evapotranspiration and streamflow percentages during 1981-2002 in the Bridge and Dato models

Model	Data Span	Land Use	ET	River Flow
BRDG	81-2002	1973	86.9%	23.0%
		1987	81.7%	25.1%
		2003	86.8%	23.0%
DATO	81-2002	1973	85.3%	20.2%
		1987	85.4%	20.2%
		2003	85%	20%

7.4.1.2 Hydrologic effects on Tikur Wuha catchment based on Bridge station

In the periods where the hydrometeorological time series were uniform, simulated streamflow was generated by using the 1973, 1987 and 2003 LULC maps while keeping all other parameters constant. Results revealed that during 1973-1987 the annual daily average streamflow increased (from 4.57 m^3/s to 5.3 m^3/s) when using LULC map of 1987 than that of 1973. Despite the notable changes in LULC in the 2003 LULC, it returned slight flow increment as compared to the flow generated using the 1973 LULC map. This may be attributed to the agroforestry practice of mixed cropping widely implemented in Wondo Genet area. Based on water balance analysis streamflow was also highly non-linear and very sensitive to rainfall input.

Table 7-5. Bridge model evapotranspiration and streamflow percentages in the first homogenous period (1973-1987)

Land Use Map	Data Span	ET%	River Flow%
1973	1973-1978	83.5	16.8
	1979-1987	87.2	17.6
1987	1973-1978	78.2	17.3
	1979-1987	81.7	18.4
2003	1973-1978	83.3	16.9
	1979-1987	87	17.5

Taking the overland flow, base flow to river and the saturated drain to river makeup the streamflow, about 17.4 percent of the rainfall is discharged to Lake Hawassa in the form of streamflow during the calibration and validation periods (see Table 7-5). Above 85 percent of the incoming water in the form of rainfall was evaporated and transpired during these periods. Similarly, Shewangizaw (2010) reported that about 85 percent was given off as evapotranspiration.

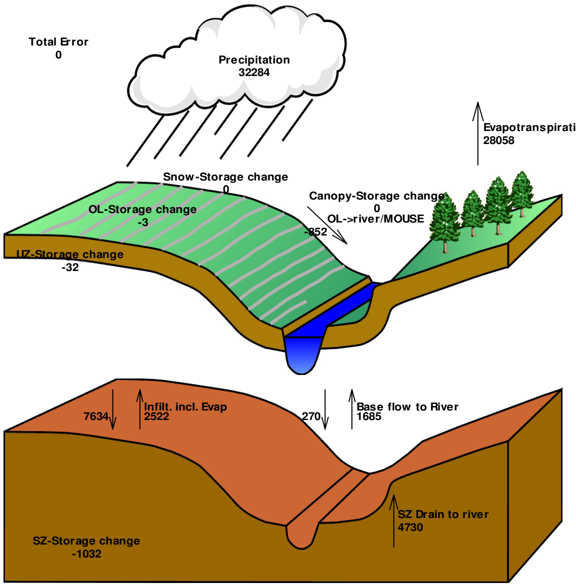
Total water balance partitioned the hydrological fluxes into streamflow, percolation, overland flow and ET proportions were being dependent on how wet the hydrological year was. The water balance assessment depicted ET accounted for the largest proportion of the hydrologic cycle. Table 7-6 shows that there were increased saturated zone drainage and base flow to river with time and with LULC change during the calibration period.

The analysis on the entire period (1973-2002) likewise had a similar trend. The negative unsaturated and saturated zone storage changes (see Figure 7.4) further asserts the decline in the surface storages and the groundwater reserves of the catchment witnessed during the later years.

Table 7-6. Cumulative water balances from the three LULC maps during calibration and validation periods (1973-1987)

Land Use Map	Data Span	Rainfall (mm)	ET (mm)	Over Land Flow (mm)	USZ Storage Δ (mm)	SZ Drain to River (mm)	Base flow to River (mm)	Base flow from River (mm)
1973	1973-1978	6788.1	5668.7	164.0	13.8	979.2	371.0	53.4
1973	1979-1987	9592.1	8361.6	258.3	394.1	1425.2	541.7	82.1
1987	1973-1978	6788.1	5307.8	136.4	-212.0	1041.3	414.5	53.4
1987	1979-1987	9592.1	7833.1	172.4	222.1	1590.5	647.4	83.4
2003	1973-1978	6788.1	5652.1	160.9	7.8	983.1	374.4	53.2
2003	1979-1987	9592.1	8343.8	250.6	398	1431.6	549.1	81.9

Water balance estimates of Tikur Wuha catchment in time span 19973-2002 for three LULC maps are given in Appendix III. Water Balance of Tikur Wuha catchment



Accumulated waterbalance from 1/1/1973 to 12/31/2002. Data type : Storage depth [millimeter].

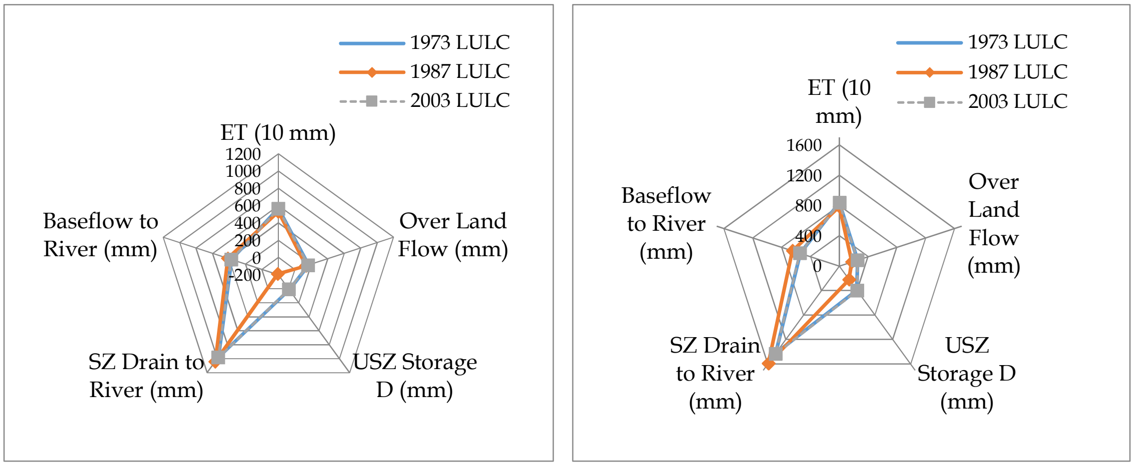
Figure 7.4. Water Balance of Tikur Wuha catchment 1973-2002 under 1973 LULC

7.4.1.3 Hydrologic effects on Tikur Wuha catchment based on Dato station

During the calibration and validation period in the Dato model, evapotranspiration proportion (82.6%) using the 1987 LULC map was the same with the Bridge model using the 1973 LULC map. The water balance analysis however indicated, components of hydrologic cycle exhibited no major variations between the LULC changes. Evapotranspiration accounted 86%, 86% and 85% for the LULC of 1973, 1987 and 2003 respectively during 1980-2002. Unsaturated zone storage change, saturated storage change, saturated zone (SZ) drain to river and overland flow (OL) percentages were 5.6, 0.45, 12.0 and 5.2 respectively for the three LULC data. According to the Dato model results, there is no impact by the LULC change.

7.4.1.4 Hydrologic effects on Tikur Wuha catchment based on the two stations

Total streamflow responded reciprocal to the evapotranspiration decrease for LULC map of 1973 to that of 1987. However, the data shows that the increase in streamflow was due to the increased saturated zone drain and base flow to river. Overland flow decreased despite the expected increase due to reduced interception. Figure 7.5 depicts that response from LULC 1973 and 2003 were similar.



(a) (b)

Figure 7.5. Chosen component water balances for (a) Calibration & (b) Validation periods

This could be attributed to the implementation new farming system in the higher altitudes of the watershed which was forested formerly, turned into cultivation but in recent times agroforestry is being practiced.

Both models presented that streamflow and evapotranspiration increased in the period 1988-2002 than 1973-1987 as a response to the land use changes. For instance, evapotranspiration increased from 84.4%, 79.0%, 84.1% to 88.2%, 83.0%, 88.1% for LULC maps of 1973, 1987 and 2003 respectively. This showed that the rest of the water balance components of the watershed have contributed to evaporation and stream flow. There was reduced unsaturated zone storage and more release from the saturated zone to the river system. This in turn would justify the fact that water bodies were endangered for extinction as was in the case of Lake Cheleleka.

Table 7-7. Water balance results (mm) of Bridge and Dato models using the three LULC maps

Model	Data Span	Total Rainfall	Land Use	ET	Over Land Flow	USZ Storage Δ	SZ Drain to River	Base flow to River	Base flow from River
BRDG	81-1987	7782.1	1973	6565.9	188	59.9	1105.1	422.5	63.9
			1987	6147.7	119	-71.7	1238.1	507.4	65
			2003	6546.9	181.6	58.3	1110.3	428	63.6
DATO	81-1987	7782.4	1973	6428.1	404.9	-721.9	887.2	188.2	38.8
			1987	6426.8	407	-724.5	887.2	188.9	38.8
			2003	6412.6	403.9	-729.5	890.1	191.9	38.7
BRDG	88-2002	15904.1	1973	14027	429	653.4	2324.3	771.7	134.9
			1987	13201.2	246.3	556.8	2659.9	982.6	134.9
			2003	14014.7	414.3	681.8	2339.1	782.2	134.2
DATO	88-2002	15904.1	1973	13786	811.5	-635.4	1955	419.5	80.4
			1987	13793.1	814.2	-627.7	1956.3	421.6	80.4
			2003	13771.2	804.7	-621.9	1965.2	430.7	80.2
BRDG	81-2002	23686.3	1973	20593.3	617.1	714.2	3429.9	1194.4	198.8
			1987	19349.2	365.4	485.9	3898.4	1490.2	199.9
			2003	20561.8	596.1	740.9	3449.8	1210.4	197.8
DATO	81-2002	23686.6	1973	20214.6	1216.6	-1356.6	2842.6	607.8	119.2
			1987	20220.3	1221.5	-1351.5	2843.9	610.6	119.2
			2003	20184.1	1208.8	-1350.8	2855.7	622.7	118.9

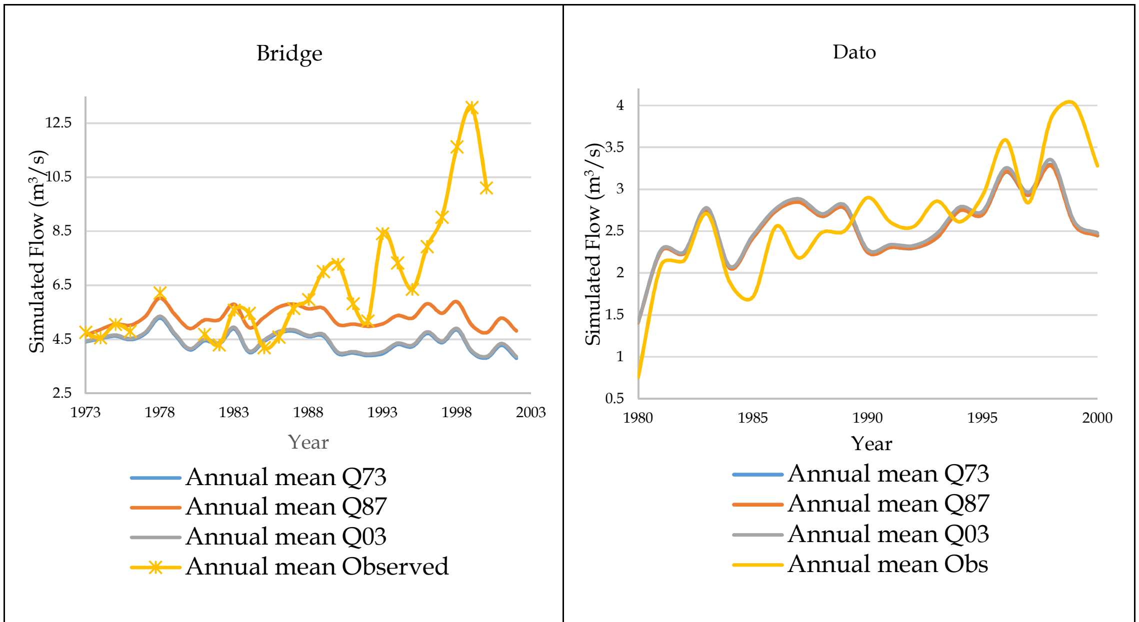
All measurements are in mm.

Cumulative water balances of the Bridge and Dato models for the homogenous periods (1981-1987 and 1981-2002) are compared in Table 7-7. During the homogenous period, the Bridge model's evapotranspiration has decreased for the 1987 LULC than that of 1973 and regained for the 2003 LULC. The Dato model on the other hand showed evapotranspiration was more or less the same for all the LULC data. While overland flow increased, unsaturated zone storage, saturated zone drain to river, base flow to river and base flow from river decreased in the Dato model than the bridge model during the same period. Unlike the Dato model, the Bridge model was able to discern the differences in the water balance of the catchment that resulted from the LULC changes in this period. Land use land cover changes affected evapotranspiration more than the rest of the components followed by saturated zone drain to river, unsaturated zone storage, base flow to river and over land flow. Base flow from river showed almost no change at all.

In the period 1988-2002, the models behaved as in the homogenous period. However, unsaturated zone storage was shown to have highly increased in the bridge model while the Dato model presented it to have extremely decreased. The latter is justified by the disappearing of Lake Cheleleka which made sense with the decrease in the saturated zone storages and flows. This can be taken as indicator that the bridge station flow measurement accuracy has been compromised in the later days.

7.4.1.5 Land use land cover change impacts on Tikur Wuha River flow

Flow simulation for the three LULC maps show that annual mean flow slightly declines with time for both models. However, the observed flow exhibited an increase of 62.1% and 49.7% over the simulated flow for the Bridge and Dato models respectively. The Bridge model indicated that the simulated annual mean flow of Tikur Wuha River increased with the change in LULC between 1973 and 1987 (Table 7-8). For instance, mean flow increases by 15.6% using the 1987 LULC than the 1973 LULC. The Dato model on the other hand, did not show notable change in simulated annual daily mean flow using the three LULC maps (see Figure 7.6). The observed flow at Tikur Wuha was higher that the simulated flows. This was an indicator for questioning the data quality at the Bridge station.



(a) (b)

Figure 7.6 Simulated flow from the three LULC data at (a) Bridge station (b) Dato village station

Table 7-8. Annual daily average simulated streamflow using LULC Maps of 1973, 1987 and 2003

Year	Annual Average Simulated flow (m^3/s)		
	LULC map of 1973	**LULC map of 1987**	**LULC map of 2003**
1973 - 1987	4.57	5.29	4.61
1988 - 2002	4.23	5.28	4.29

According to the Bridge model, graph of simulated evapotranspiration (see Figure 7.7) depicted that it followed the same pattern with the LULC change especially with the shrub and forest land class. Since this LULC class is transpiring more water than the other classes, it is reasonable that it had similar patterns. The Dato model however showed no variation in evapotranspiration across the LULC changes.

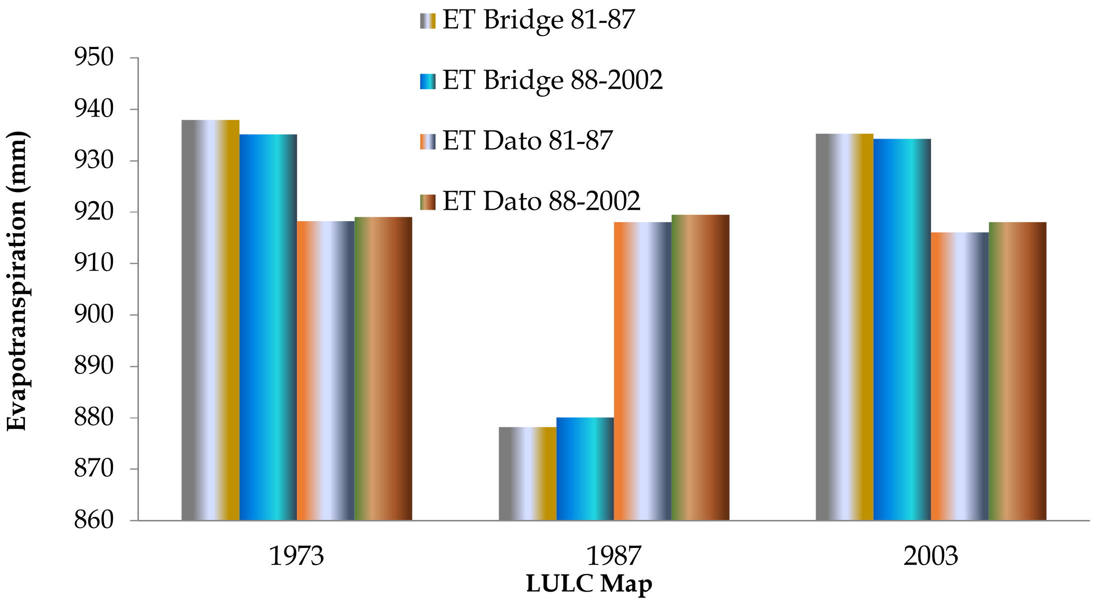


Figure 7.7. Annual evapotranspiration for Bridge and Dato models

The reference evapotranspiration calculated from the meteorological data at Hawassa shows that evapotranspiration declined towards recent times. This may be an indication that the Dato discharge may have flaws. It was explained that the quality of Bridge discharge measurement had deteriorated towards the end times. This again is very serious evidence that the discharge measurement facilities need grave evaluation.

7.4.2 Hydrological response to climate variability based on the two stations

Climate variability depicted in the non-homogeneous segments of the time series was tested for impacts in the water balance components of the catchment. This was done by keeping the LULC constant and differencing the annual average of the water balance components in the first homogeneous period (1981-1987) from the second homogeneous period (1988-2002). The data span 1981 – 2002 was used in this analysis because of the existence of data for both the Dato and Bridge stations.

Table 7-9. Climate variability impacts in the water balance differences of Bridge and Dato models using the three LULC maps

Difference between the first and the second periods							
Model	**Land Use**	**ET**	**Over Land Flow**	**USZ Storage Δ**	**SZ Drain to River**	**Base flow to River**	**Base flow from River**
BRDG	1973	-2.9	1.7	35.0	-2.9	-8.9	-0.1
	1987	1.8	-0.6	47.4	0.5	-7.0	-0.3
	2003	-1.0	1.7	37.1	-2.7	-9.0	-0.1
DATO	1973	0.8	-3.7	60.8	3.6	1.1	-0.2
	1987	1.4	-3.9	61.7	3.7	1.1	-0.2
	2003	2.0	-4.1	62.8	3.9	1.3	-0.2

All measurements are in mm.

As shown in Table 7-9, there were very negligible variations on the values of the yearly average water balance components except unsaturated zone storage. Dato model returned about 50% more storage in the unsaturated zone than the Bridge model. There was also a decline in base flow to the Tikur Wuha River depicted by the Bridge model which was not the case in the Dato model. These results were analogous for the three LULC scenarios considering both models. Therefore, this study concluded that the hydrometeorological variations observed in the time series records of the watershed were not drastically affecting the water balance components except unsaturated zone storage.

7.5 Conclusion and Recommendation

Hydrologic models using three LULC maps derived from multi-temporal satellite imageries of 1973, 1987 and 2003 were used to assess the impact of LULC changes in Hawassa watershed. Two sets of Tikur Wuha catchment MIKE SHE models based on the two flow measuring stations were developed for this purpose. Measured time series of hydrometeorological data in the period 1973–2003, soil properties and geologic data were collected from various sources and compiled as required by the modeling system to set them up. The three LULC maps served to establish land use-related input parameters. The developed models were then calibrated and validated to be used for impact assessment analyses. The MIKE SHE models were applied on the three LULC data during repeated model runs while keeping all other model parameters constant.

Water balance assessment and streamflow simulations outcomes indicated that, evapotranspiration accounted for the largest water loss of the total rainfall (85%), while the rest represents only nearly 15%. The highest water loss was noticeably obtained in the period 1988-2002. The models demonstrated that the LULC changes impacted the streamflow of Tikur Wuha River and adversely modified the different components of the catchment water balance especially the subsurface flows.

In general the effect of LULC changes on the annual water balance was moderate. Streamflow was the most susceptible to LULC change for both models of the catchment. Climate variability was found to have notable effect largely on unsaturated zone storage. Hence, the impact of climate variability was less as compared to LULC change impact on the catchment during the study period.

It was noticed that accuracy of the flow measurement in the catchment needed attention (see Figure 7.8). On one hand, flow measurement at the bridge station deteriorated with time that forced the model to overestimate saturated and unsaturated zone storages. On the other hand, the Dato model failed to distinguish

LULC change impact on streamflow. This suggests checking the accuracies of the station measurements and reestablishing the stations if need be is inevitable.

Figure 7.8. Dato village streamflow measuring station

CHAPTER 8: SYNOPSIS

This study addressed impact of climate and LULC change on Hawassa watershed in a different way than the conventional assessment method. Firstly, the hydrometeorological data were tested for trend, homogeneity and change points. Based on the change points, LULC changes were evaluated from Landsat images taken in the reference years selected to single out impacts brought about in the watershed using physically based fully distributed hydrologic model. Morphometric impact on Lake Hawassa was also studied to ascertain the extent of lake sedimentation and identify areas of immediate attention.

8.1 Trend and Time of Change Detection

Mass curve analysis, normality and independence tests, homogeneity and trend tests, and change point analyses were done on hydrometeorologic data of Hawassa watershed. Mass curve analysis showed that rainfall at the watershed exhibited no sign of change while Tikur Wuha River flow had a notable change at the beginning of 1987. Many of the hydrometeorological parameters at Hawassa were found normal but all were showing autocorrelations. Maximum, minimum and mean annual lake level, temperature, reference evapotranspiration and Tikur Wuha discharge exhibited significant increasing trend. Although rainfall at Hawassa was reported to have significant link with ENSO phenomena (Belete *et al.*, 2017; Wagesho *et al.*, 2012), there existed no trend in rainfall. Average, maximum and minimum annual potential evapotranspiration in Hawassa had a decreasing trend. The mean, maximum and minimum annual temperature exhibited an upward trend. Monthly aggregates of lake level, reference evapotranspiration and TWR flow had change points in August and September 1988, March 1989, July 1988 respectively. Temperature had November 1985, February 1995 and January 1990 for monthly maximum, minimum and mean temperature series respectively. Combining the information above, it was possible to conclude that many of the parameters exhibited change in the second half of 1988. Therefore, this study considered that time series data of 1973-1987 and 1988 to 2003 were homogenous and LULC and hydrological impact assessment investigations were based the beginning intermediate and end times of these periods.

8.2 LULC Change Detection

Land use land cover change analysis was done by comparing maps produced by supervised classification of Landsat images acquired in 1973, 1987, 2003 and 2019. The achieved overall classification accuracies were 89.5%, 95.6%, 92.5% and 95.1%, while the Kappa coefficients were 0.87, 0.95, 0.91 and 0.94 respectively.

Based on the results obtained from remote sensing and GIS applications to arrive at the LULC of the watershed, dramatic increase of 188% in built-up area was seen during the 30 years of the study period, and about 115% of this change happened between the years 1987 and 2003. Shrub and forest lands lost about 23% in coverage. About 5% area was lost by grassed wetlands and water bodies in the watershed. Agricultural land increased by about 7%. However, since the area has been dominantly cultivated, this land use class had the highest aerial increase in the watershed. During the first homogeneous period (1973-1987) grass land exhibited the highest change in declining by about 40% followed by settlement area (34.1%

increases). Even if there was a decrease in surface area of Lake Cheleleka, there was an equal amount of surface area expansion in Lake Hawassa resulting in a net zero loss or gain. The second homogenous period (1987-2003) was dominated by settlement increase of 114.8%. Grass land was the next highest by an increase of 44.9%. This increase was attributed to the conversion of some cultivated Shallo farm land into grass land. Cultivated and grassed wetland increase by 0.2% and 2.3% respectively while shrub and forest land lost 18% coverage. Notable lake surface loss was recorded during this period.

It is concluded that the LULC practices in the study area had been altered significantly in the past few decades (1973-2019). The LULC shift in the watershed area was evident by the decline in the area of water body, shrub and forest, wetland grass and grass land classes (5.5%, 62.6%, 63.9% and 36.7% respectively) and augmentation of area covered by classes of Settlements (802.9%) and Agriculture (20.5%). The LULC maps are recommended to be used as input data for the anthropologic impact assessment study.

Effects of the LULC changes were reflected on the lake level and river flows of the watershed. Lake level increased with the change in LULC in time. Lake Hawassa was proved to be endangered as was the case in Lake Cheleleka if appropriate measures are taken.

8.3 Morphometric Change Detection

Bathymetric map of Lake Hawassa (2011) was developed from primary gridded sounding data and remote sensing data using geostatistical techniques. This map provided recent hydrographic information to be compared with the 1999 bathymetric map produced by WWDSE. The comparison showed that the volume of Lake Hawassa decreased in 2011 from that of 1999. Lake surface area based on NDWI analysis and image classification showed a decreasing trend except for the period where Lake Hawassa inundate the surrounding areas. However, the study indicated that the rate of change of Lake surface area and volume were not straightforward signifying the importance of bathymetric investigation. Lake Cheleleka surface area rapidly decline to extinction.

Lake Hawassa morphometric investigation showed that the bed of the Lake was impacted by siltation. Sediment deposition areas were identified in three zones of the Lake. The northern and eastern deposition zones were dominantly areas of shore development for residential purposes whereas the western zone received sediments from fragmented farm lands where new gullies were recently developing.

8.4 Hydrological Impact Detection

Partitioning of time series into homogeneous assessment segments was made based on the results of hydrometeorologic data appraisal. Accordingly, data span 1973-1987 and 1988-2003 were found to be homogeneous independently. Therefore, the first period was used to calibrate and validate the MIKE SHE model. The second span was used to assess the impact of LULC change together with the first. Two models were built making use of datasets from the two discharge measurement posts, Bridge and Dato village stations. The models have 0.64 and 0.59 overall Nash Sutcliffe coefficients for Bridge and Dato models respectively.

Evapotranspiration account for over 85% of the total rainfall and all the rest hydrological fluxes account for 22% of the total rain falling in the catchment. Streamflow and evapotranspiration increased as a response to the land use changes. The fact that there was reduced unsaturated zone storage and more release from the saturated zone to the river system indicated the endangerment of the lake in the watershed. Generally the effect of LULC changes on the annual water balance was moderate. However, streamflow was most susceptible to LULC change for both models of the catchment. This had the impact on the amount of recharge to the groundwater which later will be reflected on the health of Lake Hawassa. The assessment also suggested that streamflow measurement is very crucial to the management decisions to be taken by the responsible authorities. Climatic variability impacted the watershed minimally.

8.5 Summary and Conclusions

In order to assess the impact of natural and anthropogenic phenomena on Hawassa watershed, this study addressed four areas of focus. These were, detecting the presence of trends and their time of change in hydro-meteorological (Climatic) variables; detecting LULC changes in the watershed; detect hydrographic change in Lake Hawassa and evaluate impact of climate variability and LULC changes on the dominant hydrological processes using coupled surface and groundwater modeling framework.

Hydrometeorological data of the watershed were found out to have gone under remarkable change with the exception of rainfall. The hydrometeorological data were sectioned into climatically homogeneous periods (1973-1987 and 1988-2003) to select LULC base images and run hydrologic models where impacts of LULC change could be singled out by differencing model responses of the changing LULC. Cultivated land was the dominant LULC class in the watershed (for all the LULC maps of 1973, 1987, 2003 and 2019 produced) with urban areas growing at alarming rate. The other LULC classes declined indicating the need for proper land management interventions. The LULC change impacts were also seen to influence the bathymetry of Lake Hawassa in which the Lake lost significant amount of volume and surface area to sedimentation. Bathymetric map of Lake Hawassa for 2011 was produced and made available. The study showed the severity of siltation and identified three intervention zones to guide soil and water conservation works in the watershed.

Hydrologic models were developed that can simulate surface and subsurface flows in the Tikur Wuha catchment reasonably well. The models had been calibrated and verified using discharge observations. The models can serve as useful tools to help diagnose climate and LULC change impacts on water resource availability in this region. The simulations showed that in the catchment water balance, evapotranspiration accounted for over 85% of the total rainfall and surface water flow was the most sensitive component to LULC changes. Changes in hydrologic fluxes in turn influenced the watershed characteristics as well.

Climatic variability was found to impact the unsaturated zone storage adversely. Therefore its impact was not as profound as the LULC change impacts. This was good news in a sense the impacts are reversible with the proper catchment management supported by sound land use policies.

It was also seen that flow measurement is very crucial in monitoring and studying the watershed. The current measurement stations required a serious reevaluation. Soil and water conservation interventions and implementing the Ethiopian conservation policies that give guide lines (Amsalu & Addisu, 2014) is crucial to safeguard this unique watershed harboring endemic as well as other fauna and flora.

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NB: APA reference style was used

APPENDICES

Appendix I. Summary of meteorological data of Hawassa watershed

Appendix Table 1. Annual Rainfall and Evapotranspiration data

Year	Rainfall (mm)				Reference Evapotranspiration (mm)			
	Hawassa	Haisawita	Wendo Genet	Yirba	Hawassa	Haisawita	Wendo Genet	Yirba
1973	743.8	1020.6	1045.7	1089.3	1739.7	1421.7	1421.7	1412.0
1974	937.3	1060.3	1044.2	1196.0	1697.1	1421.7	1421.7	1412.0
1975	826.2	1143.8	1155.2	1305.9	1660.0	1421.7	1421.7	1412.0
1976	951.4	1229.9	982.0	1247.4	1697.6	1426.3	1426.3	1416.5
1977	1226.3	1387.8	1296.2	1395.5	1601.4	1421.7	1421.7	1412.0
1978	1032.9	1358.8	1311.1	1292.9	1643.8	1421.7	1421.7	1412.0
1979	968.4	579.2	1081.6	861.4	1671.7	1421.7	1421.7	1412.0
1980	801.1	1043.9	904.5	898.5	1755.8	1426.3	1426.3	1416.5
1981	1039.7	1306.8	1135.5	1129.5	1592.5	1421.7	1421.7	1412.0
1982	991.6	1403.2	1132.8	1084.1	1559.3	1421.7	1421.7	1412.0
1983	1159.8	491.1	1313.9	1111.3	1599.4	1421.7	1421.7	1412.0
1984	724.5	1355.4	820.6	817.8	1742.6	1426.3	1426.3	1416.5
1985	904.6	1235.2	1157.5	1113.3	1736.6	1421.7	1421.7	1412.0
1986	1196.2	1078.6	1107.0	1166.8	1730.1	1421.7	1421.7	1412.0
1987	959.3	1316.4	1228.8	1514.4	1752.8	1421.7	1421.7	1412.0
1988	970.5	1038.9	1175.1	1055.9	1731.3	1426.3	1426.3	1416.5
1989	1027.3	843.7	1240.5	1157.8	1389.8	1421.7	1421.7	1412.0
1990	767.7	902.1	931.0	882.1	1388.0	1421.7	1421.7	1412.0
1991	904.3	920.3	1200.0	788.3	1360.7	1421.7	1421.7	1412.0
1992	1018.0	1311.4	1276.7	1140.5	1372.9	1426.3	1426.3	1416.5
1993	983.2	1143.1	1124.1	1217.8	1359.0	1421.7	1421.7	1412.0
1994	946.0	1088.4	1288.2	994.5	1412.5	1421.7	1421.7	1412.0
1995	1028.4	982.7	1022.4	799.0	1411.4	1421.7	1421.7	1412.0
1996	1193.6	1249.3	1252.0	1264.1	1363.5	1426.3	1426.3	1416.5
1997	1068.5	802.7	1225.1	1170.3	1414.8	1421.7	1421.7	1412.0
1998	1163.4	1321.5	1304.6	1104.9	1342.8	1421.7	1421.7	1412.0
1999	829.0	887.3	916.5	906.2	1395.2	1421.7	1421.7	1412.0
2000	842.5	1097.5	943.1	889.6	1460.4	1426.3	1426.3	1416.5
2001	1084.9	1360.8	1290.5	1257.0	1380.5	1421.7	1421.7	1412.0
2002	920.8	1080.2	995.0	1096.8	1433.7	1421.7	1421.7	1412.0
2003	868.4	1081.3	1038.9	1096.4	1422.7	1421.7	1421.7	1412.0
2004	942.6	1117.5	1035.2	1101.6	1395.7	1426.3	1426.3	1416.5
2005	1050.6	1416.2	1165.6	1338.1	1412.6	1421.7	1421.7	1412.0
2006	1222.9	1541.9	1292.3	1084.0	1375.7	1421.7	1421.7	1412.0

Appendix Table 2. Summary of annual average hydrometeorological data of Hawassa watershed

Year	Hawassa Lake Level (m)	Tikur Wuha Flow Dato(m3/s)	Cheleleka Lake Level (m3/s)	Tikur Wuha Flow Bridge(m3/s)	Average Rainfall (mm)	Max Temperature (˚C)	Wind Speed (m/s)	Sun Shine (hrs)	Total ETo (mm)	Relative Humidity (%)	Min Temperature (˚C)
1972	1.8			6.8		25.8					11.8
1973	1.2			4.8	969.94	26.8			1739.7		11.8
1974	0.8			4.6	1026.24	25.9			1697.1		11.1
1975	0.6			5.1	1078.30	25.8			1660.0		11.6
1976	0.6			4.8	1063.24	26.1			1697.6		11.7
1977	0.9				1313.24	25.6			1601.4		12.8
1978	1.7			6.2	1266.43	25.8			1643.8		12.1
1979	2.0		1.6		878.15	26.3			1671.7		12.5
1980	1.6	0.8	1.0		931.10	27.2			1755.8		12.4
1981	1.1	2.1	1.1	4.7	1175.11	26.2			1592.5		12.4
1982	1.0	2.1	1.2	4.3	1197.54	26.0			1559.3		12.9
1983	1.4	2.7	1.3	5.6	987.64	26.4			1599.4		12.6
1984	1.5	1.9	0.9	5.5	989.20	27.0			1742.6		10.6
1985	1.1	1.7	0.9	4.2	1129.09	26.4		7.2	1736.6	63.9	11.1
1986	1.2	2.6	1.1	4.6	1116.67	26.6		7.3	1730.1	64.7	11.6
1987	1.6	2.2	1.1	5.7	1200.23	27.2		7.3	1752.8	63.4	12.4
1988	1.6	2.5	1.1	6.0	1081.44	27.0		6.7	1731.3	63.3	12.4
1989	2.0	2.5	1.1	7.0	1052.40	26.5	1.0	7.1	1389.8	64.2	12.3
1990	2.1	2.9	1.1	7.3	884.58	27.2	1.0	7.0	1388.0	63.0	12.3
1991	1.6	2.6	0.8	5.8	1035.21	27.5	0.8	6.9	1360.7	62.6	12.4
1992	1.4	2.6	1.3	5.2	1231.73	27.1	0.8	7.1	1372.9	65.5	13.0
1993	2.0	2.9	1.5	8.4	1099.65	27.1	0.8	7.0	1359.0	64.7	12.3
1994	2.0	2.6	1.1	7.3	1141.48	27.8	0.9	7.1	1412.5	61.8	12.4

Year	Hawassa Lake Level (m)	Tikur Wuha Flow Dato(m3/s)	Cheleleka Lake Level (m3/s)	Tikur Wuha Flow Bridge(m3/s)	Average Rainfall (mm)	Max Temperature (˚C)	Wind Speed (m/s)	Sun Shine (hrs)	Total ETo (mm)	Relative Humidity (%)	Min Temperature (˚C)
1995	1.8	2.9	0.7	6.4	1009.63	27.8	0.8	7.4	1411.4	63.3	12.5
1996	2.2	3.6	1.0	7.9	1238.11	27.0	0.8	7.2	1363.5	66.4	12.5
1997	2.6	2.8	0.8	9.0	1040.45	27.2	0.8	7.6	1414.8	63.4	13.1
1998	3.3	3.9	1.2	11.6	1279.33	26.9	0.7	7.0	1342.8	64.0	13.7
1999	3.2	4.0	1.0	13.1	886.76	27.1	0.8	7.6	1395.2	61.1	12.4
2000	2.6	2.7	0.7	10.1	975.64	27.4	0.8	8.1	1460.4	60.7	12.4
2001	2.6	3.1	1.1		1269.93	27.2	0.7	7.4	1380.5	62.9	13.2
2002	2.6	3.4	0.8		1008.82	27.8	0.8	7.7	1433.7	60.4	13.2
2003	2.1	3.2	0.4		1016.20	27.7	0.8	7.6	1422.7	61.9	13.0
2004	1.9	3.7	1.1		1043.92	27.5	0.7	7.4	1395.7	61.3	12.9
2005	1.8	3.2	0.9		1229.11	27.6	0.8	7.6	1412.6	60.2	12.8
2006	2.0	3.0	1.3		1365.55	27.3	0.8	7.0	1375.7	65.2	13.6
2007	2.7		1.1			27.1	0.9	7.4		64.3	13.0
2008	2.7		0.9			27.3	0.9	7.0		61.7	13.3

Appendix II. Confusion matrixes and accuracy assessment measures

Appendix Table 3. Confusion matrixes and accuracy assessment (1973)

	1973 LULC Classes	**Reference Data**						**Row Total**	**User's Acc.**
		BU	CL	SFL	GL	WB	GW		
Classified Data	Built Up (BU)	53	3	2	1	0	1	60	95.45%
	Cultivated Land (CL)	5	53	0	2	0	0	60	89.04%
	Shrub & Forest Land (SFL)	0	0	52	1	1	0	54	98.46%
	Grass Land (GL)	2	4	3	56	0	2	67	93.24%
	Water Body (WB)	0	0	0	0	58	2	60	96.92%
	Grassed Wetland (GW)	0	0	3	0	1	55	59	98.53%
	Column Total	60	60	60	60	60	60	360	
	Producer's Accuracy	91.30%	94.20%	95.52%	95.83%	98.44%	95.71%		
	Overall Accuracy	90.83%							
	Kappa Coefficient	0.890							

Appendix Table 4. Confusion matrixes and accuracy assessment (1987)

	1987 LULC Classes	**Reference Data**						**Row Total**	**User's Acc**
		BU	CL	SFL	GL	WB	GW		
Classified Data	Built Up (BU)	55	3	2	1	0	1	62	95.45%
	Cultivated Land (CL)	5	54	0	2	0	0	61	89.04%
	Shrub & Forest Land (SFL)	0	0	52	2	1	0	55	98.46%
	Grass Land (GL)	0	3	3	55	0	2	63	93.24%
	Water Body (WB)	0	0	0	0	58	2	60	96.92%
	Grassed Wetland (GW)	0	0	3	0	1	55	59	98.53%
	Column Total	60	60	60	60	60	60	360	
	Producer's Accuracy	91.30%	94.20%	95.52%	95.83%	98.44%	95.71%		
	Overall Accuracy	91.39%							
	Kappa Coefficient	0.897							

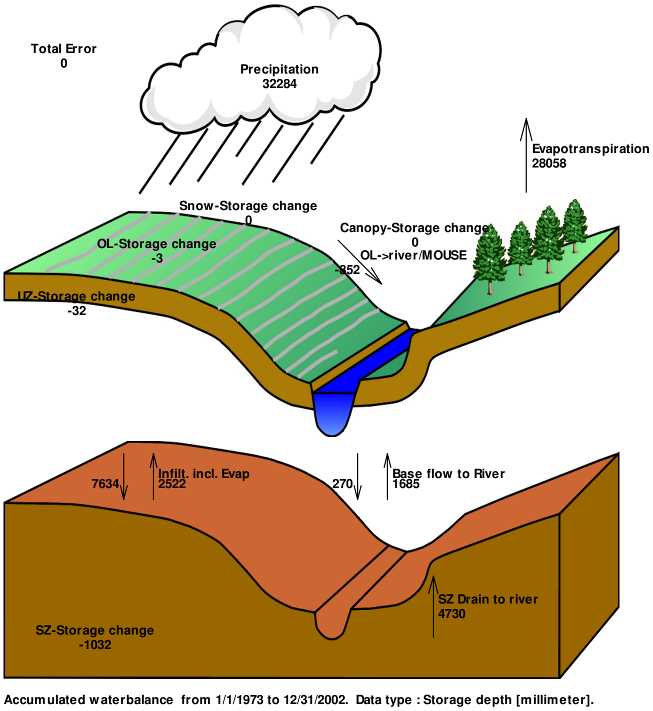
Appendix Table 5. Confusion matrixes and accuracy assessment (2003)

		Reference Data						**Row Total**	**User's Acc**
		BU	CL	SFL	GL	WB	GW		
Classified Data	Built Up (BU)	56	2	0	2	0	0	60	95.45%
	Cultivated Land (CL)	4	55	0	2	0	0	61	89.04%
	Shrub & Forest Land (SFL)	0	0	56	2	0	0	58	98.46%
	Grass Land (GL)	0	3	2	54	0	2	61	93.24%
	Water Body (WB)	0	0	0	0	59	2	61	96.92%
	Grassed Wetland (GW)	0	0	2	0	1	56	59	98.53%
	Column Total	60	60	60	60	60	60	360	
	Producer's Accuracy	91.30%	94.20%	95.52%	95.83%	98.44%	95.71%		
	Overall Accuracy	93.33%							
	Kappa Coefficient	0.920							

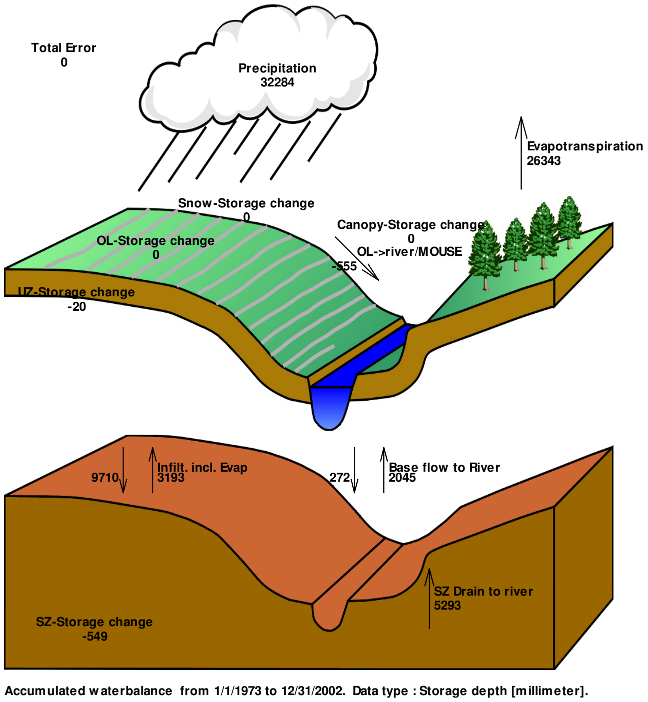
Appendix Table 6. Confusion matrixes and accuracy assessment (2019)

	2019 LULC Classes	**Reference Data**						**Row Total**	**User's Acc**
		BU	CL	SFL	GL	WB	GW		
Classified Data	Built Up (BU)	63	3	0	0	0	0	66	95.45%
	Cultivated Land (CL)	6	65	0	2	0	0	73	89.04%
	Shrub & Forest Land (SFL)	0	0	64	1	0	0	65	98.46%
	Grass Land (GL)	0	1	3	69	0	1	74	93.24%
	Water Body (WB)	0	0	0	0	63	2	65	96.92%
	Grassed Wetland (GW)	0	0	0	0	1	67	68	98.53%
	Column Total	69	69	67	72	64	70	411	
	Producer's Accuracy	91.30%	94.20%	95.52%	95.83%	98.44%	95.71%		
	Overall Accuracy	95.13%							
	Kappa Coefficient	0.942							

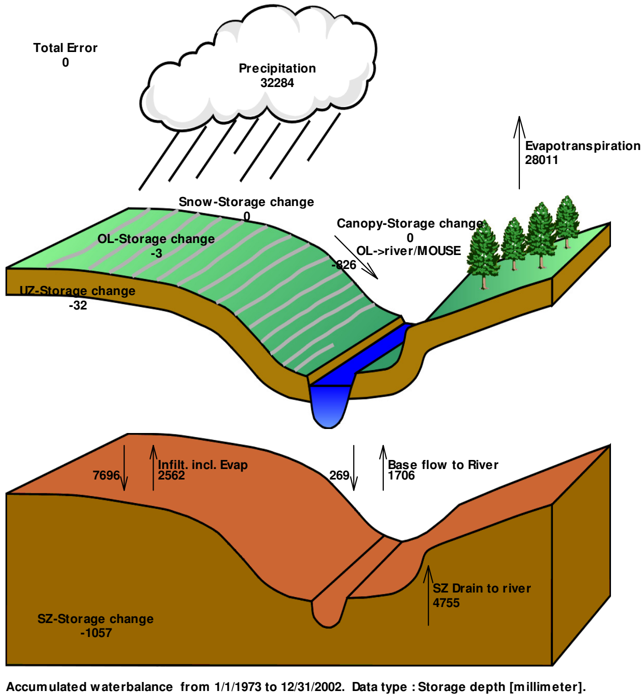
Appendix III. Water Balance of Tikur Wuha catchment



(a)



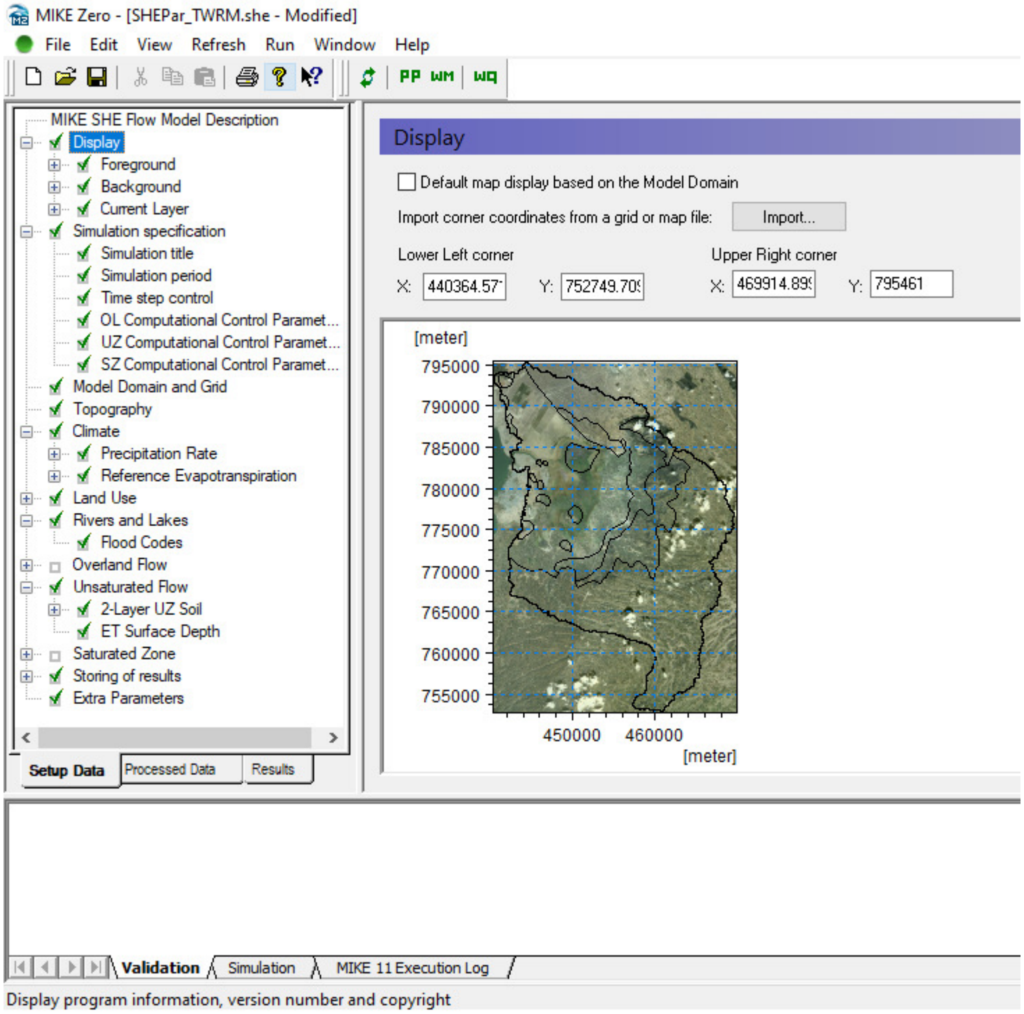
(b)



(c)

Appendix Figure 1. Water Balance of Tikur Wuha catchment for the years 1973-2002 (a) Based on 1973 LULC (b) Based on 1987 LULC (c) Based on 2003 LULC

Appendix IV. MIKE SHE Model setup and some data



☐ Default map display based on the Model Domain

Import corner coordinates from a grid or map file:

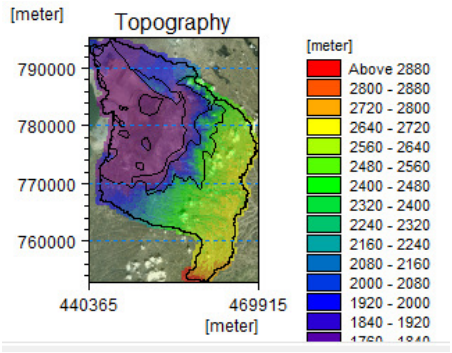
Lower Left corner X: 440364.57 Y: 752749.70

Upper Right corner X: 469914.89 Y: 795461

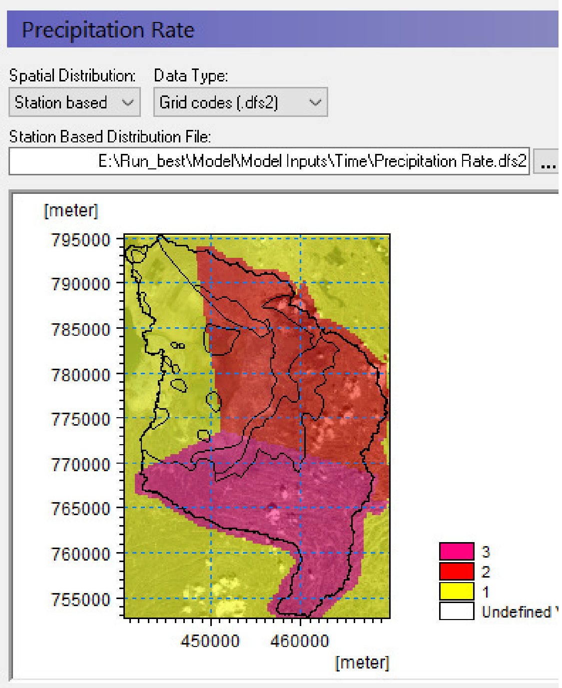
Display program information, version number and copyright

MIKE SHE- MIKE 11 Model Snapshot

Simulation Spesification



Digital Elevation Model



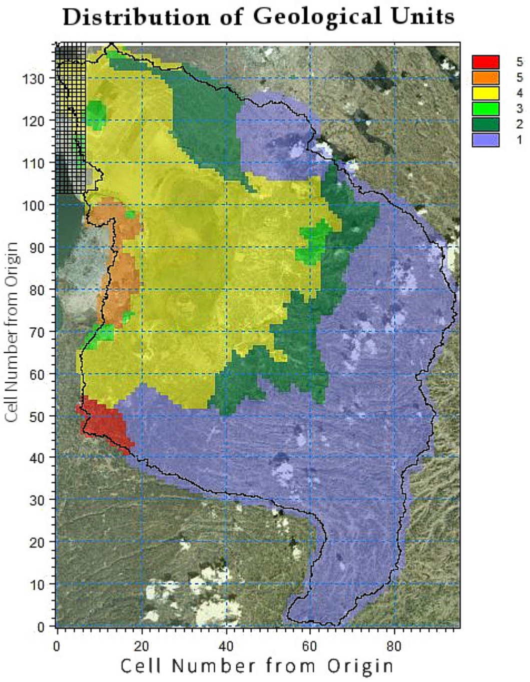
Precipitation Rate

Spatial Distribution: Station based

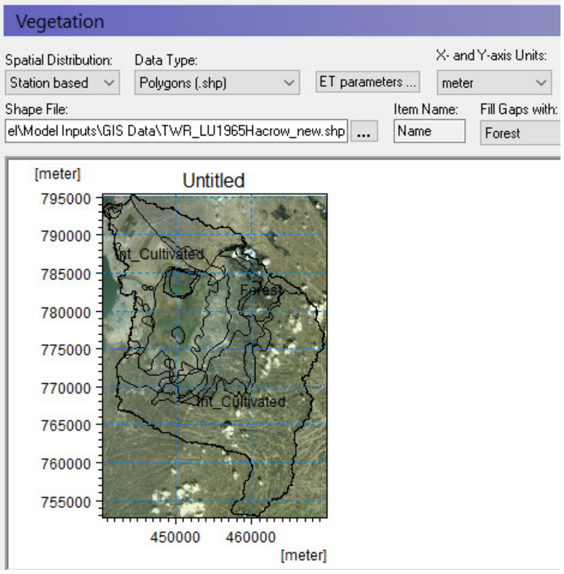
Data Type: Grid codes (.dfs2)

Station Based Distribution File: E:\Run_best\Model\Model Inputs\Time\Precipitation Rate.dfs2

Climatic data - Rainfall



Geological unit distribution



Vegetation

Spatial Distribution: Station based

Data Type: Polygons (.shp)

ET parameters ...

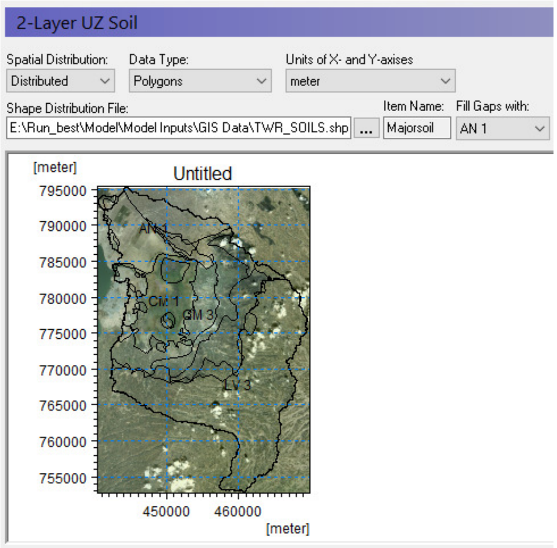
X- and Y-axis Units: meter

Shape File: el\Model Inputs\GIS Data\TWR_LU1965Hacrow_new.shp

Item Name: Name

Fill Gaps with: Forest

LULC - Vegetation



2-Layer UZ Soil

Spatial Distribution: Distributed

Data Type: Polygons

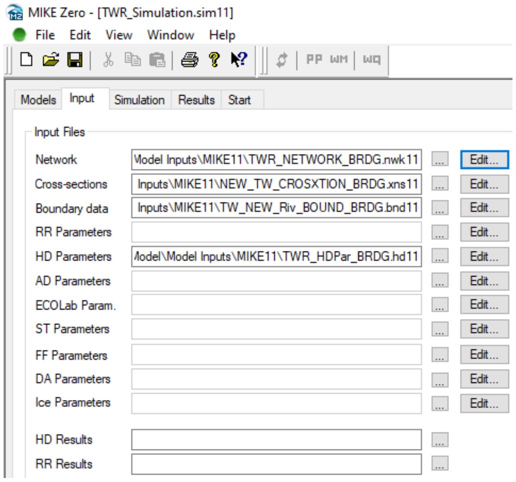
Units of X- and Y-axises: meter

Shape Distribution File: E:\Run_best\Model\Model Inputs\GIS Data\TWR_SOILS.shp

Item Name: Majorsoil

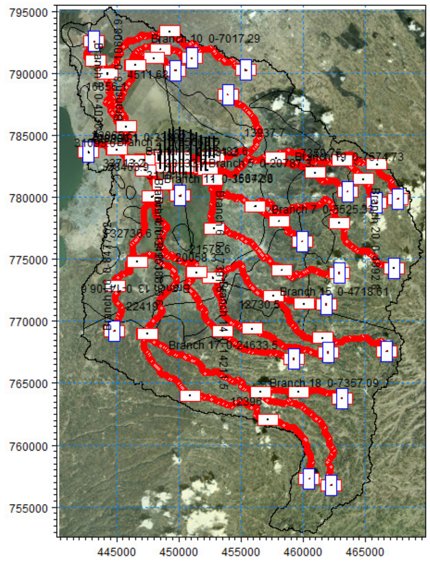
Fill Gaps with: AN 1

Soils

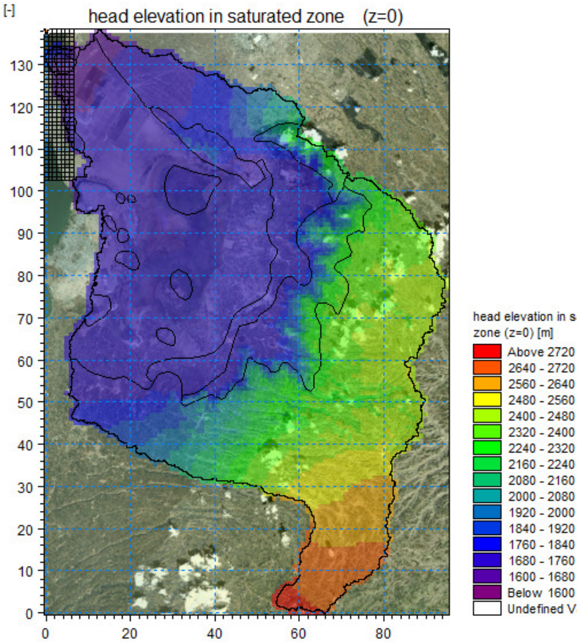


Network	Model Inputs\MIKE11\TWR_NETWORK_BRDG.nwk11
Cross-sections	Inputs\MIKE11\NEW_TW_CROSXTION_BRDG.xns11
Boundary data	Inputs\MIKE11\TW_NEW_Riv_BOUND_BRDG.bnd11
RR Parameters	
HD Parameters	lodel\Model Inputs\MIKE11\TWR_HDPar_BRDG.hd11
AD Parameters	
ECOLab Param.	
ST Parameters	
FF Parameters	
DA Parameters	
Ice Parameters	
HD Results	
RR Results	

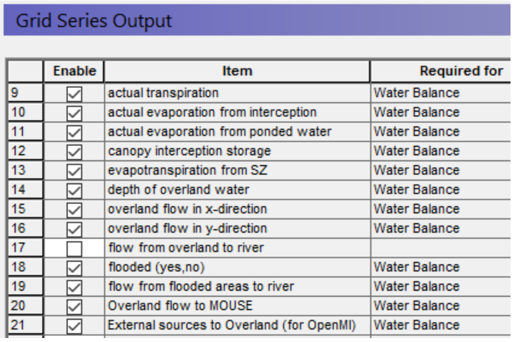
MIKE 11 Set Up



River network and Cross-sections



Initial Hydraulic head


Grid Series Output

	Enable	Item	Required for
9	☑	actual transpiration	Water Balance
10	☑	actual evaporation from interception	Water Balance
11	☑	actual evaporation from ponded water	Water Balance
12	☑	canopy interception storage	Water Balance
13	☑	evapotranspiration from SZ	Water Balance
14	☑	depth of overland water	Water Balance
15	☑	overland flow in x-direction	Water Balance
16	☑	overland flow in y-direction	Water Balance
17	☐	flow from overland to river	
18	☑	flooded (yes,no)	Water Balance
19	☑	flow from flooded areas to river	Water Balance
20	☑	Overland flow to MOUSE	Water Balance
21	☑	External sources to Overland (for OpenMI)	Water Balance

Output Time Series

Appendix Figure 2. Snapshot of some input data to MIKE SHE model

Appendix V. Published article

https://www.mdpi.com/2073-4441/10/5/625

water

MDPI

Article

Morphometric Change Detection of Lake Hawassa in the Ethiopian Rift Valley

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Abstract: The Ethiopian Rift Valley lakes have been subjected to environmental and ecological changes due to recent development endeavors and natural phenomena, which are visible in the alterations to the quality and quantity of the water resources. Monitoring lakes for temporal and spatial alterations has become a valuable indicator of environmental change. In this regard, hydrographic information has a paramount importance. The first extensive hydrographic survey of Lake Hawassa was conducted in 1999. In this study, a bathymetric map was prepared using advances in global positioning systems, portable sonar sounder technology, geostatistics, remote sensing and geographic information system (GIS) software analysis tools with the aim of detecting morphometric changes. Results showed that the surface area of Lake Hawassa increased by 7.5% in 1999 and 3.2% in 2011 from that of 1985. Water volume decreased by 17% between 1999 and 2011. Silt accumulated over more than 50% of the bed surface has caused a 4% loss of the lake's storage capacity. The sedimentation patterns identified may have been strongly impacted by anthropogenic activities including urbanization and farming practices located on the northern, eastern and western sides of the lake watershed. The study demonstrated this geostatistical modeling approach to be a rapid and cost-effective method for bathymetric mapping.

Keywords: bathymetry; Ethiopian rift; geostatistics; Lake Hawassa; lake morphometry

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1. Introduction

Lakes are among the most fragile environments due to anthropogenic effects alongside natural phenomena that can trigger rapid environmental changes to their ecosystems. For instance, declining lake levels were indicative of climate-driven changes [1]. Soil erosion and sediment deposition as well as pollution from municipal, industrial and agricultural waste are among the major menaces to which lakes are exposed [2]. Severe erosion and sedimentation may result in diminishing lake size and, in some cases, can cause the disappearance of a lake body and induce changes in its fauna and flora population. Because lakes and reservoirs are low points in the landscape, they receive water and sediment inputs from the surrounding terrestrial catchment and the upwind airsheds [3]. These inputs can influence the environs positively or negatively and bring about environmental change resulting

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