The impact of sedimentation and climate variability on the hydrological status of Lake Hawassa, South Ethiopia

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Dedicated to:

My queen `Simegn Asmare´, my children `Fikir Mulugeta´ & `Nuhamin Mulugeta´, and my late mother `Yeshumnesh Alemayehu´

Acronyms and abbreviations

AMO	Atlantic Multidecadal Oscillation
AnnAGNPS	Annualized Agricultural Non-point Sources
AR	Autoregression
CL	Confidence limit
CSE	Conservation Strategy of Ethiopia
DEM	Digital Elevation Model
DPSIR	Drivers-Pressures-State-Impact-Response
EIA	Environmental impact assessment
ENSO	El Niño-Southern Oscillation
ETo	Potential evapotranspiration
GIS	Geographic Information System
HSG	Hydrologic Soil Group
IPPC	Intergovernmental Panel on Climate Change
ITCZ	Inter-tropical Convergence Zone
m.a.s.l	meter above sea level
MER	Main Ethiopian Rift
MJO	Madden-Julian Oscillation
MK	Mann-Kendall
MODIS	MODerate-resolution Imaging Spectroradiometer
MoWR	Ministry of Water Resources
MPSIAC	Modified Pacific Southwest Inter Agency Committee
MUSLE	Modified Universal Soil Loss Equation
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NBS	Net Basin Supply
NEP	North-East Pacific
NNSMP	National non-point source monitoring program
NOAA	National Oceanic and Atmospheric Administration
NP	North Pacific Index
NSE	Nash-Sutcliffe efficiency
ONI	Oceanic Niño Index
PDA	Personal Digital Assistant
PDO	Pacific Decadal Oscillation
PSIAC	Pacific Southwest Inter Agency Committee
RSI	Regime Shift Index
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
SPOT5	Satellite Pour I´Observation de la Terre 5
SRTM	Shuttle Radar Topography Mission
SST	Sea Surface Temperature
TLU	Tropical Livestock Unit
UNEP	United Nations Environmental Protection
USBR	United States Bureau of Reclamation
USLE	Universal Soil Loss Equation
VCF	Vegetation Continuous Fields
WRDB	Water resources development bureau
WWDSE	Water works design and supervision enterprise

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ABSTRACT

Lake Hawassa is a topographically closed lake in the Central Main Ethiopian Rift Valley. The water level of this lake has been rising significantly with an average rate of 4.9 cm/year over the study period (1970-2010). The cause of this rise is not yet sufficiently investigated. The main target of this study is to investigate causal variables for lake level variability in general, and its resultant rise in particular. The study is based on two main hypotheses. The first is concerned with the effect of climate variability on the lake level variability; and the second is related to the effect of sedimentation on the storage capacity of the lake.

The first hypothesis (the effect of climate variability) was investigated through the application of diverse statistical techniques. It comprises the coherence analysis to study the linear relationship between the 3.4 ENSO index and lake level changes. A sequential regime shift algorithm was employed to investigate the variations in the mean values of some selected hydro-climatic variables. Trend test was also used to investigate the variability of the hydro-climatic variables overtime. A simple water balance approach was applied to simulate the lake level variability so as to examine how the model behaves throughout the study period.

The second hypothesis (the effect of sedimentation) was approached by conducting a new bathymetric survey. The result of the new survey was compared with the existing bathymetric map of 1999. The Pacific-Southwest Inter-Agency Committee (PSIAC) model was also employed to identify the "hot-spots" of sediment production in the watershed. In this semi-quantitative model, nine factors affecting sediment yielding the watershed were characterized, rated, and an overlay analysis was performed. Participatory assessment of anthropogenic factors that affect the hydrological status of the lake was conducted through the application of DPSIR (Drivers-Pressures-State-Impact-Response) analytical framework.

The result of the coherence analysis between the monthly lake level changes and the corresponding changes in the ENSO index reveals that the two variables have significant linear relationship over frequencies ranging from 0.13 to 0.14 cycles/month or 1.56 to 1.68 cycles/year. This corresponds to a dominant average periodicity (coincident cycle) of about 7.4 months. Furthermore, the result of sequential regime shift detections show that most of the significant change points coincide with the occurrences of ENSO events and climate shifts. Generally, the lake level tends to be high during El Niño and low during La Niña years. The typical example is the coincidence of extreme historical maximum lake level to the strongest El Niño event of the century that occurred in 1997/98. The coincidence of climate regime shift in the Pacific Ocean in 1976/77 with an equivalent regime shift in the lake level and rainfall records of this period is considered as additional evidence. The study further reveals the existence of sequential regime shifts in stream flow, runoff coefficient, and lake evaporation which clearly coincide with the occurrences of ENSO phenomena.

Results of the Mann-Kendall trend analyses also reveal the significant increasing trend of the lake level and streamflow. On the contrary, decreasing trend of evaporation was observed while rainfall exhibits no trend over the study period.

The long-term increasing trend of streamflow from Tikur Wuha sub-watershed without the corresponding increment in rainfall is found to explain the role of land use/cover changes at least in modifying the impact of climate.

The application of simple spreadsheet water balance model estimates the long-term (1986-2006) average annual magnitudes of the water balance components as follows: over-lake precipitation (89 Mm^3), evaporation from the lake surface (132 Mm^3), streamflow from the Tikur Wuha sub-watershed (94 Mm^3), and streamflow from the un-gauged sub-watershed (77 Mm^3) and storage changes (3 Mm^3).

Comparison of the two bathymetric maps shows that the average accumulated sediment between the years 1999 and 2010 was estimated as 14 ± 5cm or 13.3 $x10^6$ m^3. Assuming a constant rate, the mean annual average rate of sedimentation in the lake is about 1.2 cm/year or 1.1 $x10^6$ m^3. Accordingly, the mean annual reduction in storage capacity of the lake due to siltation is 0.08 %.

The attempt to link sediment yield estimate of the bathymetric approach with the estimates of the PSIAC model results in a considerable disagreement as the former estimates 967 m^3/km^2/year whereas the latter estimates the sediment yield to be in the range of 95-250 m^3/km^2/yr.

The result of participatory assessment of anthropogenic factors and review of previous studies shows that anthropogenic factors show considerable impact on the hydrological status of the lake. Sedimentation and increased runoff are perceived as pressures (immediate causes) for the lake level rise (state). These pressures are perceived to arise from drivers (land use changes, deforestation and misuse/mistreatment of land resources). These drivers in turn had resulted from indirect drivers that comprised population growth and density, agricultural development, the use of wood as fuel, socio-economic changes, and the existing land tenure system. The interesting finding of this assessment of anthropogenic factors is the presence of promising policy instruments (responses) that support the integrated management of the lake and the watershed. The failure of implementation of these policy instruments is the commonly complained issues among the stakeholders.

KURZFASSUNG

Der Hawassa-See ist ein Endsee im afrikanischen Grabenbruch, dessen Wasserstand im Zeitraum dieser Studie (1970-2010) jährlich im Durchschnitt um 4,9 cm gestiegen ist. Der Grund für diesen Anstieg ist noch nicht ausreichend erforscht. Das Hauptziel dieser Studie ist die Untersuchung der Ursachen für die Variabilität des Seewasserstandes im Allgemeinen und für den beobachteten Anstieg insbesondere. Dieser Arbeit liegen zwei Hypothesen zugrunde. Die erste bezieht sich auf die Auswirkungen der Klimavariabilität und die zweite auf die Auswirkung der Sedimentation auf die Speicherkapazität des Hawassa-Sees.

Für die Untersuchung der ersten Hypothese (Auswirkung der Klimavariabilität) wurden verschiedene statistische Verfahren eingesetzt, darunter die Kohärenzanalyse, um die lineare Beziehung zwischen dem 3.4 ENSO-Index und der Wasserstandsänderung zu prüfen. Der sequential regime shift algorithm wurde verwendet, um zu untersuchen, ob die Kipppunkte der Mittelwerte ausgewählter hydro-klimatischer Variablen mit dem Auftreten bzw. der Intensität der ENSO-Ereignisse übereinstimmen. Weiterhin wurde eine Trendanalyse durchgeführt, um die zeitliche Variabilität klimatischer Parameter zu bestimmen. Mittels eines einfachen Wasserbilanzverfahrens wurden die Wasserstandsänderungen simuliert, um das Modellverhalten im Untersuchungszeitraum zu analysieren.

Für die Analyse der zweiten Hypothese (Sedimentationseffekt) wurde eine neue bathymetrische Untersuchung durchgeführt und mit einer existierenden Bathymetrie aus dem Jahr 1999 verglichen. Das Pacific-Southwest Inter-Agency-Committee-Modell (PSIAC) wurde für die Bestimmung von „Hot-Spots“ der Sedimentproduktion eingesetzt. In diesem Modell werden neun Faktoren der Erosion und Sedimentation im Einzugsgebiet berücksichtigt, flächenhaft berechnet und überlagert. Abschließend wurde eine partizipative Bewertung der beeinflussenden anthropogenen Faktoren im Rahmen der DPSIR-Methode (Drivers-Pressures-State-Impact-Response) durchgeführt.

Das Ergebnis der Kohärenzanalyse zwischen monatlichen Wasserstandsänderungen und den entsprechenden ENSO-Indices zeigt, dass die beiden Variablen eine signifikante lineare Beziehung im Frequenzbereich von 0,13 bis 0,14 Zyklen/Monat bzw. 1,56 bis 1,68 Zyklen/Jahr aufweisen. Dies entspricht einer dominierenden mittleren Periodizität von ca. 7,4 Monaten. Darüber hinaus zeigen die Ergebnisse der sequential regime shift detection, dass die überwiegenden Kipppunkte der ENSO-Ereignisse und der Klimaparameter übereinstimmen. Der Seewasserstand tendiert in El Niño-Jahren zu höheren und in La Niña-Jahren zu niedrigeren Werten. Ein typisches Beispiel ist die Übereinstimmung des historisch höchsten Seewasserstandes mit dem stärksten El Niño-Ereignis des letzten Jahrhunderts im Winter 1997/1998. Eine weitere Evidenz ist die Übereinstimmung der Verschiebung des Klimaregimes im pazifischen Ozean 1976/1977 mit einer entsprechenden Verschiebung des Seewasserstände und der Niederschläge im gleichen Zeitraum. Die Untersuchung zeigt auch die Existenz von weiteren Regimeverschiebungen in Abfluss, Abflussbeiwert und Evaporation in Übereinstimmung mit ENSO-Ereignissen.

Die Ergebnisse der Mann-Kendall-Trendanalyse zeigen eine Übereinstimmung zwischen Seewasserstand und gemessenem Zufluss, wohingegen die Evaporation abnimmt und der Niederschlag keinen Trend zeigt.

Die langfristige Zunahme der beobachteten Zuflüsse am Pegel Tikur-Wuha ohne Änderung des Niederschlags ist ein Hinweis auf die Bedeutung von Landnutzungs- und Landbedeckungsänderungen im Einzugsgebiet.

Die Anwendung einer einfachen Tabellenkalkulation ergibt die langfristigen (1986-2006) mittleren Jahresbilanzen: Niederschlag über dem See (89 Mm^3), Evaporation des Sees (132 Mm^3), Zufluss des Tikur-Wuha Einzugsgebietes (94 Mm^3), und Zufluss des nicht instrumentierten Einzugsgebietes (77 Mm^3) sowie Speicheränderung (3 Mm^3).

Der Vergleich der beiden Bathymetrien ergibt eine Sedimentakkumulation in der Zeit von 1999 bis 2010 in Höhe von 14 ± 5cm oder 13.3 $x10^6$ m^3, was einem mittleren Wert von 1.2 cm/a oder $1.1x10^6$ m^3 entspricht. Dies bedeutet einen Verlust an Speichervolumen in Höhe von 0.08% pro Jahr.

Beim Versuch, die Ergebnisse der Bathymetrie (967 $m^3/km^2/a$) mit denen des PSIAC Modells (95-250 $m^3/km^2/a$) zu vergleichen, werden klare Unterschiede deutlich.

Die Analyse vorheriger Studien und die teilnehmende Bewertung der anthropogenen Einflussfaktoren zeigen einen deutlichen Einfluss derselben auf die Hydrologie des Sees. Sedimentation und zunehmender Gebietsabfluss werden als Belastung (pressure) für den Seewasserstand (Status, state) angesehen. Diese Belastung ist eine Folge verschiedener Treiber (drivers: Landnutzungsänderung, Abholzung, unangemessene Nutzung der Landressourcen). Diese direkten Treiber werden von indirekten Treibern wie Bevölkerungswachstum, landwirtschaftliche Entwicklungen, Feuerholznutzung, sozio-ökonomische Änderungen sowie den existierenden Besitzverhältnissen beeinflusst. Interessanterweise existieren vielversprechende politische Instrumente (response), die das integrierte Management des Sees und seines Einzugsgebietes unterstützen. Das Versagen der Implementierung dieser politischen Instrumente wird von den betroffenen Stakeholdern beklagt.

Chapter 1. Introduction

1.1. Background information

A lake is generally defined as an inland body of fresh or saline water, appreciable in size (i.e. larger than a pond), and too deep to permit vegetation (excluding submergent vegetation) to take root completely across its expanse (Schertzer et al., 2012). They are subjected to multiple interacting stressors (Christensen et al., 2006) such as atmospheric, meteorological, geological, hydrological and astronomical influences (Altunkaynak, 2003). The human-induced changes are also found to affect the hydrology of lakes in many parts of the world.

One of the most significant and broadly impacting effects of climate variability on lakes is the changes in water level. Such changes reflect an alteration of the lake water balance, which can result from changes in: precipitation, surface runoff, ground water flow, and evaporation from the lake surface (Elsawwaf and Willems, 2012; Lenters et al., 2005). The water in a lake is balanced by the basic hydrological relationship in which the change in water storage is governed by the water input and output to the system (Limgis, 2001).

In the 1960s, lakes throughout East Africa were rising (Lamb, 1966) resulting from a series of remarkably wet years (Flohn, 1987; Nicholson, 1995). The spatial extent and the magnitude of fluctuations were considered as a signal to major global climate change (Lamb, 1966). According to Arnell et al. (1996) and Bergonzini (1998), African lakes are known to be very sensitive to climate variations with special sensitivity of closed lakes. The impact of non-climatic factors on water level variability was also reported by different scholars in Ethiopia, such as Görner et al. (2009) and Belay (2009).

In addition to climatic and non-climatic factors, the type of lake can also influence the water-level fluctuation character of a lake (Deganovsky and Getahun, 2008). For instance, lakes without outlets (called closed or terminal lakes) fluctuate in a greater degree as compared to open lakes (Langbein, 1961). The Ethiopian Rift Valley Lake Basin contains such terminal lakes that make the basin hydrologically sensitive. These terminal lakes are also sensitive to pollution by constantly taking pollutants without chances of releasing them. Xu (2011), Zhao et al. (2009), Milliman et al. (2008) and many other researchers concluded that climate change and human activities are the main driving forces that affect the hydrological status of a given lake. However, the discrimination between these two causes is still one of the major challenges in hydrology (Yang et al., 2012).

The Ethiopian Rift Valley (*figure 1.1*) is characterized by a chain of lakes varying in size, hydrological and hydrogeological settings. The water levels of some of these lakes showed dramatic changes in the last few decades (Alemayehu et al., 2006).

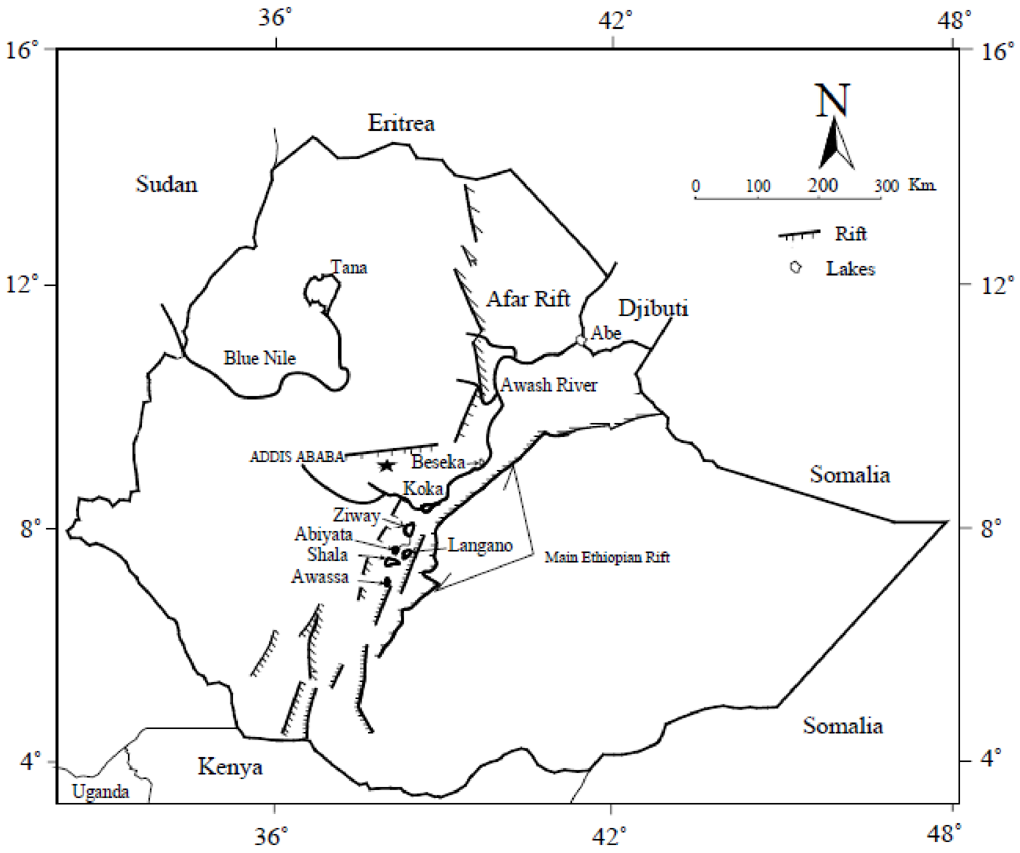


Figure 1.1. Locations of the Ethiopian Rift Valley lakes [Source: Alemayehu et al. (2006)]

The lakes in the Rift Valley are situated within three sub-basins: Awash basin (Lake Koka, Beseka, Gemari, Abe), which is located in the Northern Main Ethiopian Rift (MER), the lakes region (Lake Ziway, Langano, Abiyata, and Shalla) occupying a central part of the MER, and the Southern basin (Lake Hawassa, Abaya, Chamo, and Chewbahir). Hydrologically, the basins form separate units, but hydrogeologically they form a unique system within the rift due to the underground interconnection by NE-SW aligned regional faults (Belay, 2009; Alemayehu et al., 2006).

Lake Hawassa has been experiencing a progressive rise in water level during the past two decades (1981-1998) (Gebreegiziabher, 2004; WWDSE, 2001). The concern of this rise achieved its peak in the aftermath of the extreme flooding of the surrounding area as a result of extreme rise in 1998/99. It was because of this problem that the regional government funded an extensive studies conducted by WWDSE (2001) and WRDB (2007). Regarding the lake level rise, WWDSE (2001) explained that it was caused by deforestation which increased the runoff and siltation of the lake. However, Ayenew and Gebreegiziabher (2006) argued that the justifications are speculative rather than supported by scientific data. Another recent project was undertaken between 2008-2010 by Ministry of Water Resources with the aim of generating a development master plan for Ethiopian Rift Valley Basin in general (MoWR, 2008; 2009; and 2010). The governmental funding of the above three projects indicates the level of concern of policy makers towards the management of water resources in the region. These projects produced extensive information including the first bathymetry map of the lake, land use dynamics, soil and geological classifications, gully networks, and supportive information about the lake. They were development-oriented than dealing with scientific arguments.

There were earlier researches to understand the hydrology of Lake Hawassa and many studies associated the causes of the water-level rise of Lake Hawassa with climate changes (Lamb et al., 2002; Ayenew, 2006; Deganovsky and Getahun, 2008; Gebreegziabher, 2004; WWDSE , 2001; MoWR, 2008; Bewketu, 2010). Other researchers considered the problem as resulting from land use changes that in turn affect the runoff generation mechanism (Lamb et al, 2002; Gebreegziabher, 2004; Ayenew, 2004; MoWR, 2008; Bewketu, 2010). Less number of studies reported the role of sedimentation process into the lake (Esayas, 2010; Gebreegziabher, 2004; Geremew, 2000). The involvement of tectonic processes that affect the ground water flow regime is also recognized by Ayenew (2006), WWDSE (2001) and others. Generally, the underlying cause of the water level rise of Lake Hawassa is still a spot of confusion.

1.2. Problem statement

Over the past few years, several researchers have studied the long-term water balance of Lake Hawassa, such as Gebreegiziabher (2004), Ayenew (2004), Deganovsky and Getahun (2008), WWDSE (2001), Ayenew and Gebreegiziabher (2006), Gebremichael (2007), and Shewangizaw (2010). Land use/cover changes have also been studied by Wagesho et al.

(2012), Beetle (2009), and WWDSE (2001). Despite the number of studies and their importance, the cause of Lake Hawassa's water level rise has not been concluded and not yet explicitly investigated.

Limitations of previous studies:

(1) Previous studies focused primarily on long-term variations in the lake level which have disadvantage of obscuring particular temporal responses of the lake to extreme events. A better insight could have been grasped if the analyses had focused on both long-term variations (trends) and temporal extreme events (regime shift) simultaneously. A trend is likely to continue in the future but does not necessarily change the stationarity of the system; but a regime shift is likely to persist until a new regime shift takes place (Villarini et al., 2011);

(2) The implicit assumptions of the so-called stationarity (stability of mean values over time) of hydro-climatic variables can be erroneous unless the presences of shifts in mean values are statistically tested and the causes of those shifts assessed. Change points violate stationarity and so their identification becomes an important issue (Breaker, 2007; Wagesho et al., 2012, and Box and Jankins, 1970);

(3) No previous attempt was made to study the impact of lake-bed sedimentation on the storage capacity of the lake; and

(4) Some of the previous studies analyzed part of the story and their results should be synthesized in a logical way to show the cause-effect chain of the main environmental problems by applying a suitable analytical model, such as DPSIR framework.

1.3. Overall objectives of the thesis

The general aim of this research is to investigate the effect of natural and anthropogenic factors on the temporal variability of Lake Hawassa water level. Even though the specific objectives are within the respective chapters, the following list compiles the overall objectives:

- To test the coherence between Sea Surface Temperature (SST) anomalies and lake level variability;
- To test the presence of significant variability over-time (trend) and variability across-time (regime shift) of the hydro-climate variables (lake level, rainfall, stream flow, and evaporation);
- To simulate the long-term variability of the lake level using spreadsheet water balance model;
- To quantify the effect of sedimentation on the storage capacity of the lake by conducting new bathymetry and comparing the results with the existing one;
- To assess the linkage of in-lake sedimentation to the watershed characteristics by applying PSIAC model;
- To synthesize the preliminary cause-effect chain responsible for the lake level rise by employing the Drivers-Pressures-State-Impact-Response (DPSIR) analytical framework.

1.4. Thesis architecture and general approach

This thesis contains nine chapters where the first three cover "general introduction", "description of the study area", and "literature review" consecutively. As shown in *figure 1.2*, *chapter four* deals with an investigation into the impact of climate shifts and ENSO phenomena on the hydrological status of Lake Hawassa; *chapter five* presents simulation of the long-term lake level variability and computation of the magnitudes of water balance components. Moreover, *chapter six* is about an investigation of the effect of recent sedimentation on the storage capacity of the lake; whereas *chapter seven* is about tracing the hot-spots of sediment sources in the watershed. Finally, *chapter eight* deals with an assessment of the anthropogenic factors that affect the hydrology of the lake in a preliminary and qualitative manner while *chapter nine* presents a synthesis of the causal-links by linking natural and anthropogenic factors prevailing in the hydrosystem in a comprehensive way.

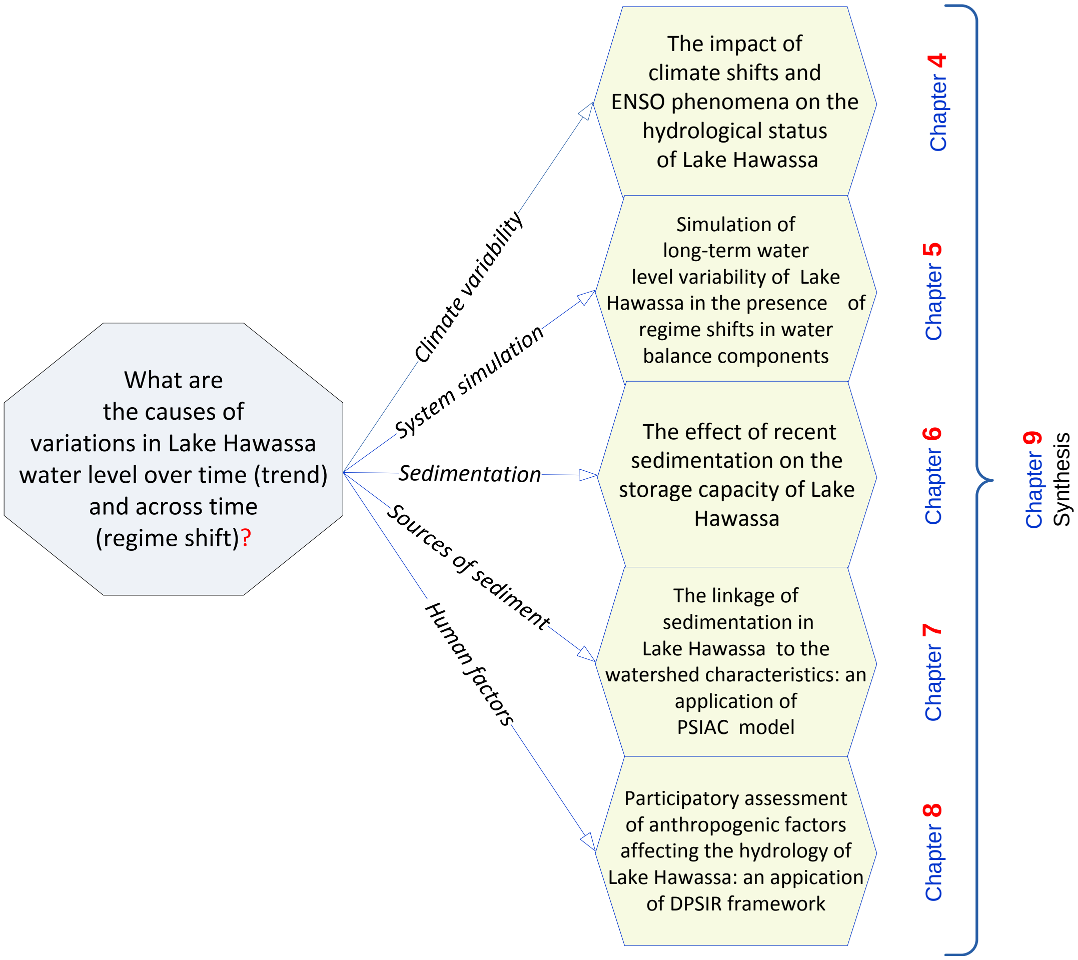


Figure 1.2. Thesis architecture and general approach

Chapter 2. Description of the study area

2.1. Location

Lake Hawassa watershed is located in the central North-East of the Ethiopian Rift Valley Basin (*figure 2.1*) and covers an area of 143,651 ha. It contains five sub-watersheds: Dorebafena-Shamena, Wedesa-Kerama, Tikur Wuha, Lalima-Wendo Kosha and Shashemene-Toga. The geographical co-ordinates of the watershed are $6^{0}45^{1}$ to $7^{0}15^{1}$ North and $38^{0}15^{1}$ to $38^{0}45^{1}$ East latitude and longitude respectively. The city of Hawassa, named after the lake, is located at 275 km south of the capital city-Addis Ababa and is established in the very eastern shore of the lake (MoWR, 2010).

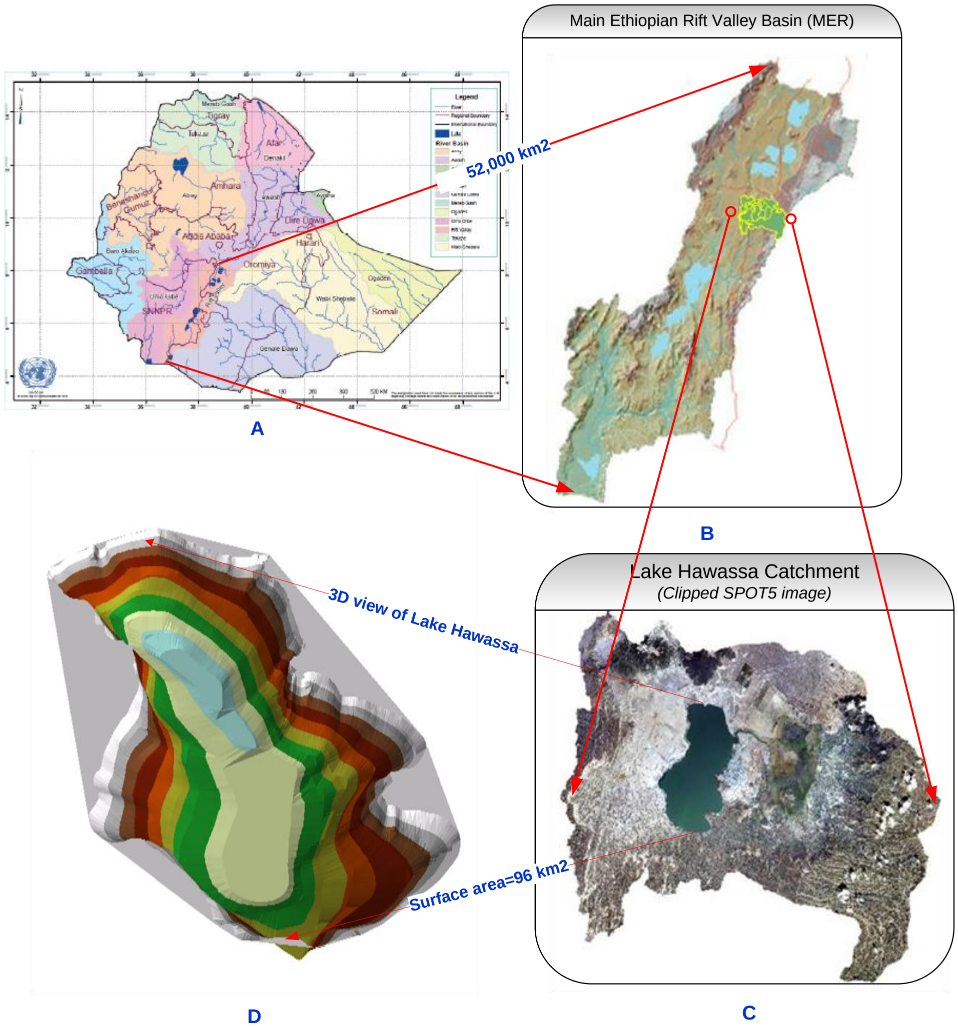


Figure 2.1. Maps of the study area at different scales

A: The 12 river basins of Ethiopia [source: Vilalta (2010)] ;

B: The Main Ethiopian Rift Valley basin [source: MoWR (2010)];

C: Lake Hawassa watershed as clipped from SPOT5 satellite image [source: own study];

D: 3D view of Lake Hawassa as generated by ArcGIS10 from the 1999 bathymetry map [source: own study]

2.2. Climate and Agro-ecology

According to Legesse et al. (2003), the watershed is characterized by three main seasons. The long rainy season in the summer from June-September is known locally as Kiremt and is primarily controlled by the seasonal migration of the inter-tropical convergence zone (ITCZ), which lies to the north of Ethiopia at this period. The wet period (locally named as Kiremt) represents 50-70% of the mean annual total rainfall. The dry period (locally named as baga) extends between October and February when the ITCZ lies to the south of Ethiopia (Legesse et al., 2004). During March and May, the "small rain" season (locally named as belg) occurs when about 20-30% of the annual rainfall falls. The climate in the area varies from dry to sub-humid according to the Thornthwaite's system of defining climate or moisture regions (Dessie, 1995).

As computed from the long-term (1973-2010) rainfall record of Hawassa meteorological station, the annual average magnitude is computed to be 961 mm and distributed as 50% for Kiremt (June-September); 20% for baga (October-February) and 30% for belg season (March-May). *Figure 2.2* shows the long-term average monthly distribution of rainfall and temperature at Hawassa meteorological station.

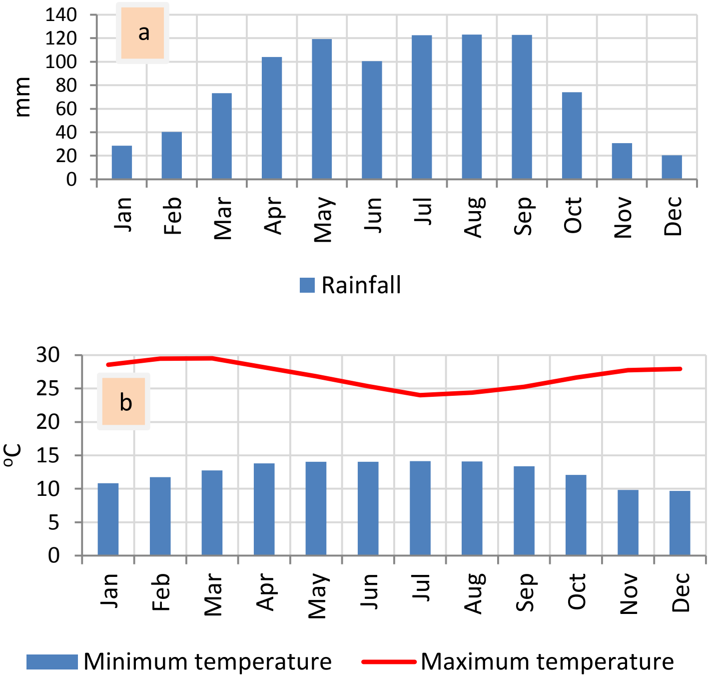


Figure 2.2. Distribution of monthly rainfall (a) and temperature (b) at Hawassa Station

The isohytal map of the watershed is shown in *figure 2.3* and the rainfall time series of the five meteorological stations in and around the watershed is shown in *figure 2.4*.

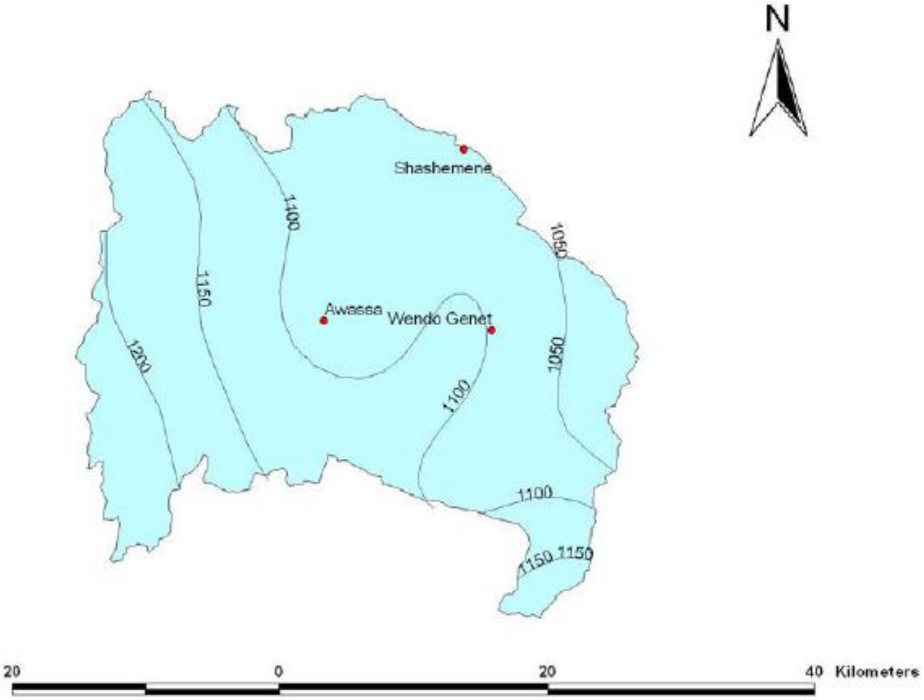


Figure 2.3. Isohytal map of Lake Hawassa watershed [Source: Shamo (2008)]

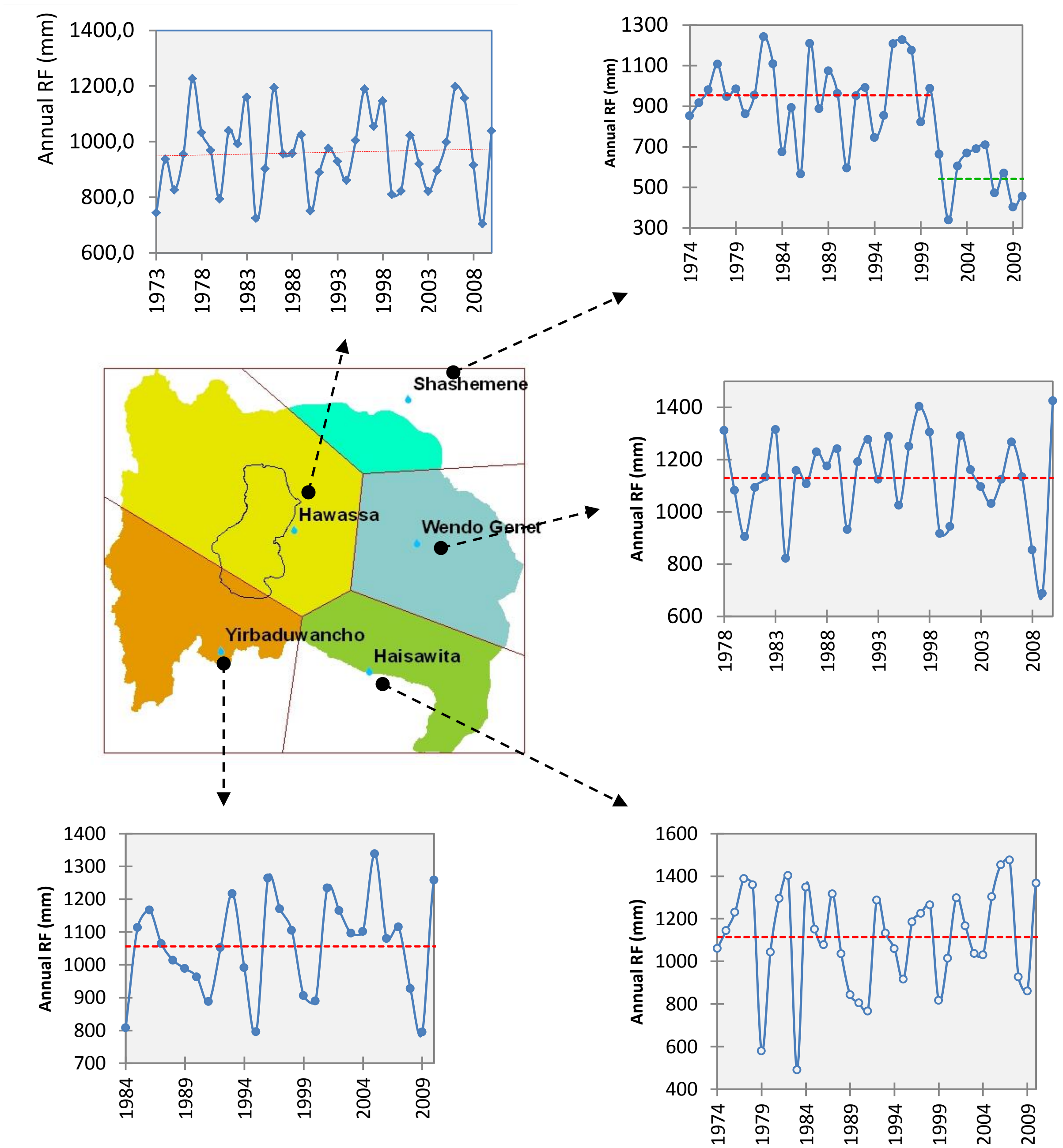


Figure 2.4. Partitioning of the watershed by Thiessen´s polygon (the red lines show average annual rainfall values. The green line for Shashemene station shows the presence of change in mean values as tested by Pettit's homogeneity statistics that detect single breaking point in a series) (The raw data was obtained from the local Meteorology Agency)

2.3. Topography

Majority of the watershed is flat to gently undulating but bounded by steep escarpments. The altitude ranges from 1,680m at Lake Hawassa to 2,700m on the Eastern escarpment: an altitude range of 1,020m. Most slopes (56%) are flat to gentle (0-8%) with a further 33% moderately sloping (8-30%) and only 5% steep to very steep (>30%) (MoWR, 2010). *Figures 2.5*, *2.6*, and *2.7* demonstrate the topographical variations in the watershed.

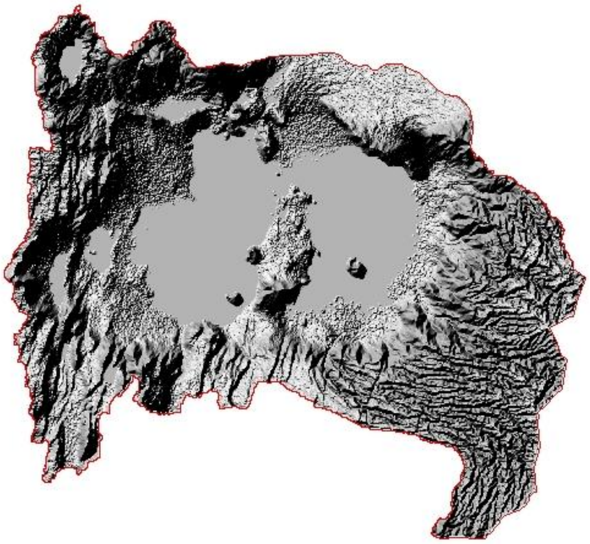


Figure 2.5. Hill shade view of the watershed landscape as processed from DEM (The unprocessed SRTM DEM of 30 x 30 m resolution was obtained from Ministry of Water Resources)

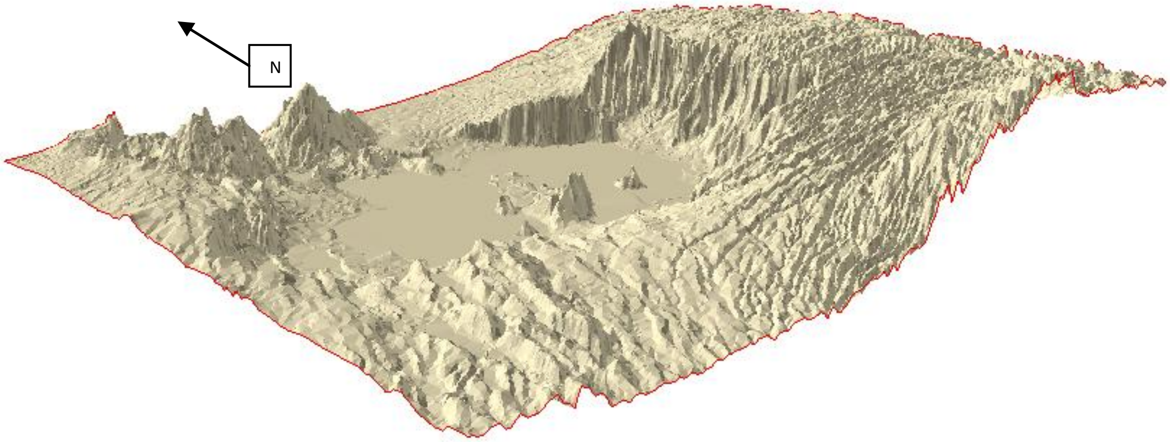


Figure 2.6. Three dimensional view of topographic diversity of the watershed (Elevations are exaggerated to some extent) (The unprocessed SRTM DEM of 30 x 30 m resolution was obtained from the Ministry of Water Resources)

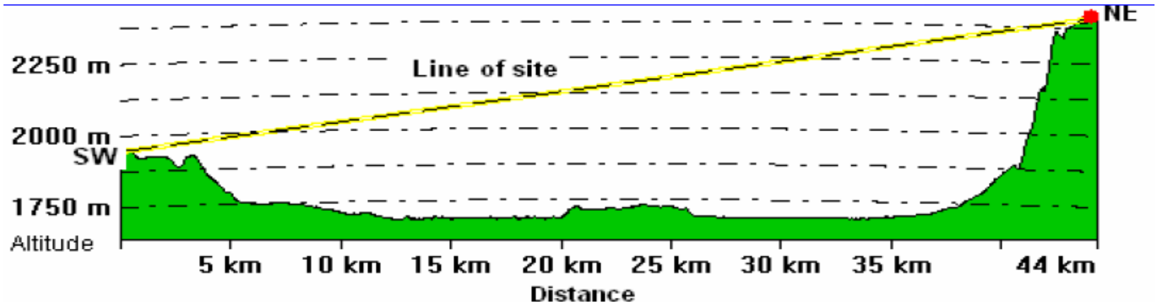


Figure 2.7. Elevation range of Lake Hawassa watershed [Source: Abraham (2007)].

2.4. Soils

Twelve soil types are identified in the watershed (MoWR, 2010) as shown in *figure 2.8* and described in *table 2.1*.

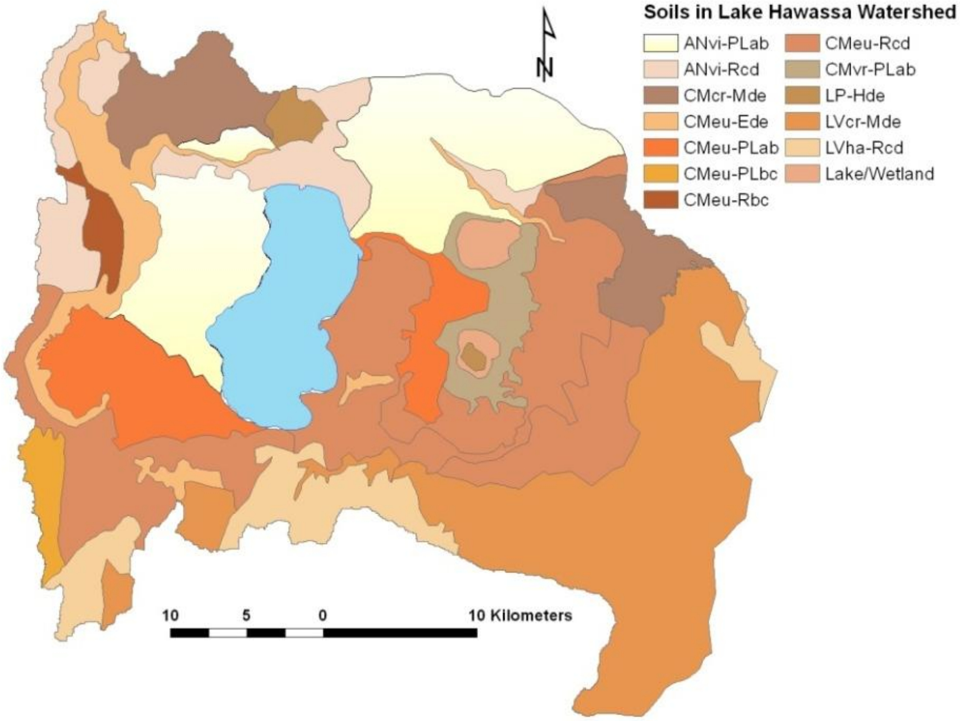


Figure 2.8. Soil types of the watershed [Source: MoWR (2010)]. For details see *table 2.1*.

Table 2.1. Description of soil types in Lake Hawasssa watershed

	Soil type code	Soil type description
1	LVcr-Mde	Well drained; deep to very deep; dark brown to dark reddish brown; fine and medium textured; moderate, fine to coarse sub angular blocky structured chromic luvisols (eutric) developed on medium to high gradient mountains with slope of 8-30%.
2	CMeu-Ede	Excessively drained; moderately deep to deep (gravely and pumice below 60cm); very dark grayish brown and very dark gray; coarse textured; weak, very fine crumb and massive structured vitric Andosols developed on level plain land form with slope of 0-2%.
3	CMeu-Rcd	Well drained; deep to very deep; medium textured; weak to moderate fine and medium sub angular blocky structured; slightly to non-calcareous eutric cambisols developed on rolling plain with a dominant slope range of 5-15%.
4	LVha-Rcd	Well drained; deep to very deep; dark brown to dark reddish brown; fine and medium textured; weak to moderate medium sub angular blocky structured; non-calcareous haplic luvisols developed on rolling plain with a dominant slope range of 5-15%.
5	CMeu-PLab	Well drained; very deep; dark brown over very dark grayish brown; medium textured; weak, medium and coarse sub angular blocky and single grain structured eutric cambisols developed on level plain land form with slope of 0-2%.
6	CMeu-PLbc	Well drained; very deep; dark brown over very dark grayish brown; medium textured; weak, medium and coarse sub angular blocky and single grain structured eutric cambisols developed on level plain land form with slope of 2-5%.
7	ANvi-PLab	Excessively drained; moderately deep to deep (pumice below 45cm); very dark grayish brown; coarse textured; weak, medium crumb and massive structured vitric Andosols developed on level plain with slope of 0-2%.
8	CMcr-Mde	Well to excessively drained; moderately deep; dark reddish brown; fine and medium textured; weak to moderate fine and medium sub angular blocky structured; non calcareous chromic cambisols developed on a very steep topography with slope >8%.
9	ANvi-Rcd	Well to excessively drained; moderately deep to very deep; dark brown to dark yellowish brown; medium and coarse textured; weak fine and medium sub angular blocky structured vitric Andosols developed on rolling plain (0-15% slope) with few to many fine pumice gravels.
10	CMvr-PLab	Very poorly drained; deep to very deep; very dark grey to black; fine and medium textured; moderate, medium sub angular blocky structured non-calcareous vertic cambisols developed on flat topography (0-2%) of alluvial plain landforms.
11	CMeu-Rbc	Well drained; deep to very deep; medium textured; weak to moderate fine and medium sub angular blocky structured; slightly to non-calcareous eutric cambisols developed on rolling plain with dominant slope range 2-8%).
12	LP-Hde	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%.

[Source: MoWR (2010)]

2.5. Land use/cover

According to MoWR (2010), land use in the watershed is dominated by cultivation which occupies 61% of the total area (or 66% of the land area) with intensive cultivation. The major land cover splits into smallholder cultivation (95%) of which 31% is cereals and perennials (CI3) and 64% cereals only (CI4) and mechanized cultivation (5%) most of which is state owned rather than private. Intensive cultivation with perennial crops occurs in the eastern hills with cereal cultivation dominating the western, southern and northern areas.

Other important land covers include disturbed and plantation forests in the Wendo Koshe hills and around Wendo Genet comprising 3% of the area; dense and open shrubland in the Wendo Koshe hills and west of Cheleleka comprising 6%, grassland (11%) comprising open grassland in the Wendo Koshe hills (3%), in association with marshland at Cheleleka (4%), in association with moderate smallholder cultivation in the Eastern hills (3%) and wooded grassland (1%) in the eastern hills.

Table 2.2. Types of land cover in Lake Hawassa watershed

Land cover	**Land cover [ha]**	**% of sub-basin**	**% of sub-basin land area**
Urban – U	2,531	1.76	1.88
Intensive Mechanized Cultivation (Private) CIMP	1,015	0.71	0.76
Intensive Mechanized Cultivation (State) CIMS	3,287	2.29	2.45
Intensive Smallholder Cultivation CI3	27,664	19.26	20.59
Intensive Smallholder Cultivation CI4	56,055	39.02	41.73
Total Intensive Smallholder Cultivation	**88,021**	61.27	65.53
Disturbed High Forest – FD	3,599	2.51	2.68
Plantation Forests – FP	328	0.23	0.24
Dense Shrubland – SD	2,104	1.46	1.57
Open Shrubland – SO	5,995	4.17	4.46
Open Grassland – GO	3,534	2.46	2.63
Open Grassland with moderate smallholder cultivation – GO/CM3	4,520	3.15	3.37
Open Grassland and Marshland - GO/MA	5,333	3.71	3.97
Wooded Grassland- GW	1,559	1.09	1.16
Marshland – MA	2,335	1.63	1.74
Open Woodland - WO	422	0.29	0.31
Dense Woodland - WD	5,744	4.00	4.28
Bare Eroded Land with scattered vegetation – EES	7,913	5.51	5.89
Bare Rock – ER	388	0.27	0.29
Total land	134,328	93.51	100
Water	9,324	6.49	
Watershed total	**143,651**	100	

[Source: MoWR (2010)]

2.6. Geology

According to MoWR (2010), the watershed forms the Corbetti caldera with the steep western and eastern escarpments of the caldera walls (*figure 2.9*). The majority of the watershed, the flat caldera floor, is composed of lacustrine sediments of Pleistocene age, evidence of the gradual desiccation and infilling of the former Lake Shallo. The Wendo Koshe hills to the north-west of Lake Hawassa are composed of pumice, unwelded tuffs, obsidian and pitchstone while other hills (Alge, Kike, Kuwe etc) and the steep escarpment immediately to the north of

Lake Cheleleka are rhyolitic and trachrytic lava flows. The hills forming the eastern escarpment are composed of Nazret silicicvolcanics comprising ignimbrites, unwelded tuffs, ash flows, rhyolites and trachytes while the land to the east of the Wendo Koshe hills is underlain by rocks of the Dino formation comprising ignimbrites, tuffs, water lain pyroclastics and occasional lacustrine beds.

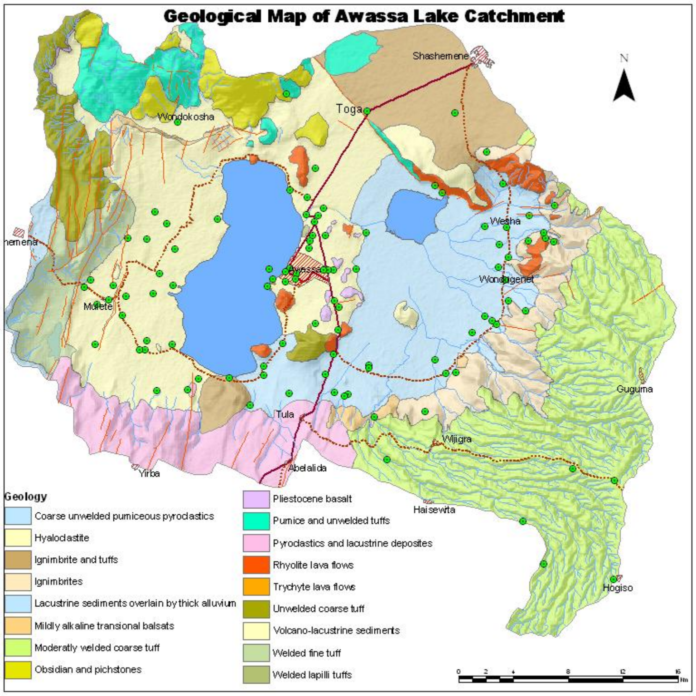


Figure 2.9. Geological map of Lake Hawassa watershed
[The red lines are the main roads crossing the watershed and the green dots are well points and not relevant in our case] [Source: WRDB (2007)]

2.7. Morphology of Lake Hawassa

Lake Hawassa is the smallest and the highest in altitude among the Great Ethiopian Rift Valley lakes (1680 m.a.s.l) and located at the geographic coordinates of Lake $7^{1}06^{0}$ N and $38^{1}33^{0}$ E between the Ziway-Shalla lakes to the north and Lakes Chamo and Abaya to the south. The lake lies within a nested caldera complex and is predominantly underlain by highly faulted ignimbrites and other silicic pyroclastic deposits (Kazmin, 1979 *as cited in* Lamb et al., 2002).

When we compare the elevation (*figure 2.10*) of Lake Hawassa (1680 m) with lake Ziway (1636 m), Langano (1585 m), Abiyata (1578 m), Shalla (1550 m) and Abaya and Chamo

(~1180m) (Gebreegziabher, 2004), it is possible for ground water to flow from Lake Hawassa to low lying lakes when hydrogeological condition permits.

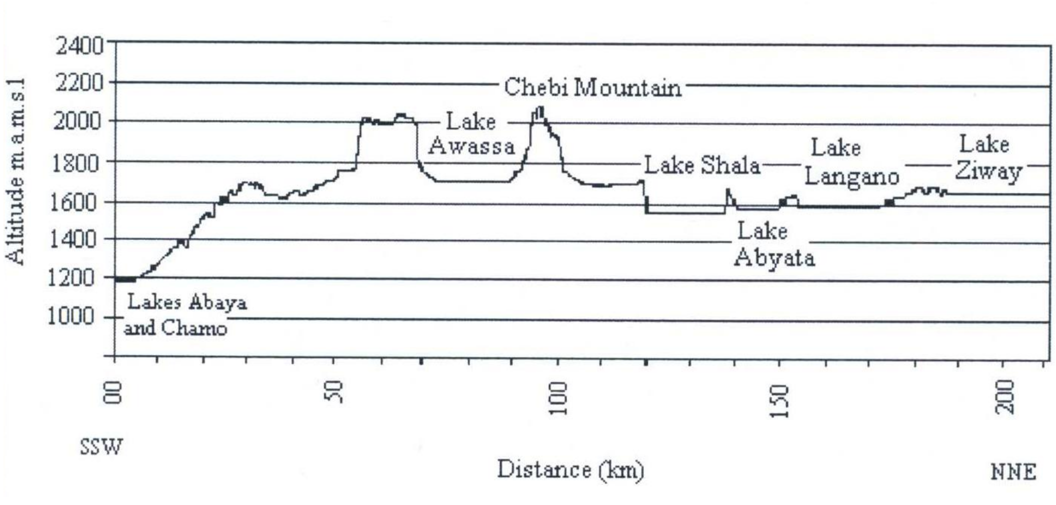


Figure 2.10. Elevation diversity of some Rift Valley lakes [Source: Gebreegziabher, 2004)]

The bathymetry survey of this research, which was conducted on January 2011, revealed that the maximum depth of the lake is 23.4 m and an average depth of 13.3 m. As extracted from satellite imagery, the length of north-to-south axis is 16 km and the east-west axis is 8 km. The water storage capacity of the lake is 1.36 km^3 (Ayenew et al., 2007). The elevation-area-volume curve of the lake is shown in *figure 2.11*.

Table 2.3. Summary of physical characteristics of Lake Hawassa

	Parameters	Size and location	References
1	Watershed area (including the lake)	1436.5 km^2 *@ Lat. $6^0 45^1$ to $7^0 15^1$North and* *@ Long. $38^0 15^1$ to $38^0 45^1$East*	MoWR (2010)
2	Maximum lake depth	23.4 m (*on Jan. 2011*) *@ Lat. 7.082019 deg. and* *Long. 38.45225 deg.*	Own study
3	Average lake depth	13.3 m (*on Jan. 2011*)	Own study
4	Lake surface area	96 km^2	Own study
5	Water storage volume	1.36 km^3	Ayenew et al. (2007)
6	Residence time	1.3 year	Ayenew et al. (2007)
7	Lake Surface area (m^2) (rating curve)	$= 4*10^6$ x d+ $9*10^6$ (where d is the actual depth of the lake m)	Gebreegziabher (2004)
8	Lake volume (m^3) (rating curve)	$= 2*10^6$x d^2+ $1*10^7$d-$5.95*10^7$	Gebreegziabher (2004)

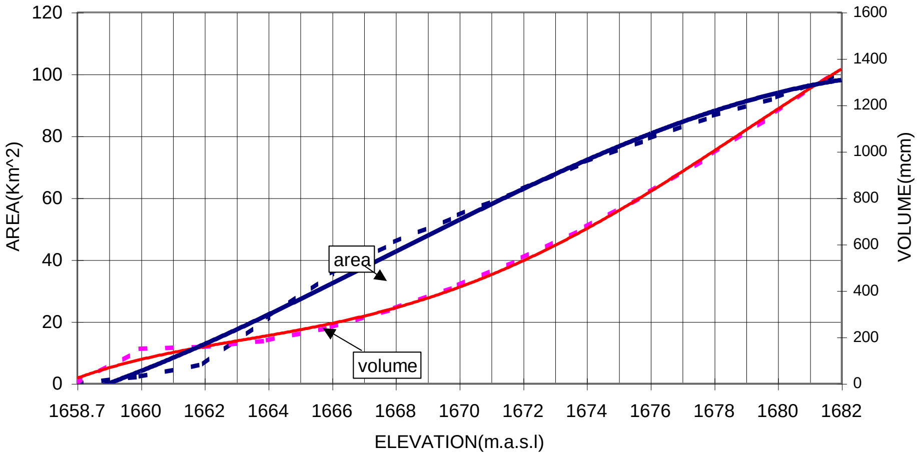


Figure 2.11. Elevation-area-volume curve for Lake Hawassa [Source: WWDSE (2001)]

Chapter 3. Characterization of the water level variability of the Main Ethiopian Rift Valley (MER) lakes

3.1. Introduction

Water level variability of a given lake results from water exchange characteristics within its watershed (Vuglinskiy, 2009). Lake levels fluctuate naturally in response to climatic and hydrological factors within natural amplitudes (Zohary and Ostrovsky, 2011) as far as they are undisturbed by external forces such as climate anomalies or anthropogenic factors. Scheffer and Carpenter (2003) also remarked that the usual state of affairs in nature is to fluctuate around some stable average. The seasonal and annual water level fluctuation of lakes is a common phenomenon in every lake. Such fluctuations are usually due to the differences between precipitation and evaporation in that specific season (Kinshiro, 1974). These dynamics are controlled by the balance between inputs and outputs of water, which are in turn controlled by the hydrological processes (Hayashi and Kamp, 2007). These natural fluctuations are an inherent feature of lake ecosystems and essential for the survival and well-being of many species that have evolved to suit their life cycle to those fluctuations (Gasith and Gafny, 1990).

In the Main Ethiopian Rift Valley region, there has been no increasing/declining precipitation trend for the last 50 years except for the inter-annual and seasonal variations (Ayenew, 2004). This kept the level of some lakes constant, with little or no change (Ayenew, 2007) but some of the lakes in the region experienced either an increasing or decreasing trend (Belay, 2009; Ayenew, 2004; Gebreegiziabher, 2004). These fluctuations are disturbing the stability of the ecosystems, putting serious impacts on the lives of many animals and plants around the lakes (Bewketu, 2010). Reviewing the characteristics of lake level variability in the region is relevant to this study in providing an insight into the similarity or dissimilarity of such variability among the lakes in the region. The hypotheses of this study arise from this review.

3.2. Objectives of the chapter

The aim of this chapter is to characterize the lake level variability of Rift Valley lakes in general and Lake Hawassa in particular. The dominant processes controlling the lake level variability are reviewed. Such characterization is expected to identify research gaps and provide information while designing the hypotheses of the main thesis work. Diverse particularities of lake level regimes in the Rift Valley Basin are intended to answer the question “what is common to these lakes?".

The lakes under consideration are: (1) Lake Ziway, (2) Lake Langano, (3) Lake Abiyata, (4) Lake Shalla, (5) Lake Beseka, (6) Lake Hawassa, (7) Lake Abaya, and (8) Lake Chamo.

3.3. Methodology

3.3.1. Description of the study area and characteristics of the lakes

The Rift Valley Lakes Basin (RVLB) is one of the eleven major river basins in Ethiopia with a total area of approximately 52,000 km^2 (MoWR, 2010). The basin is characterized by a chain of lakes varying in size, hydrological and hydrogeological settings (Alemayehu, et al., 2006). It constitutes seven main lakes: Lake Ziway, Lake Langano, Lake Abiyata, Shalla, Lake, Lake Abaya, and Lake Chamo (*figure 3.1)* where all are located south of the Ethiopian capital Addis Ababa.

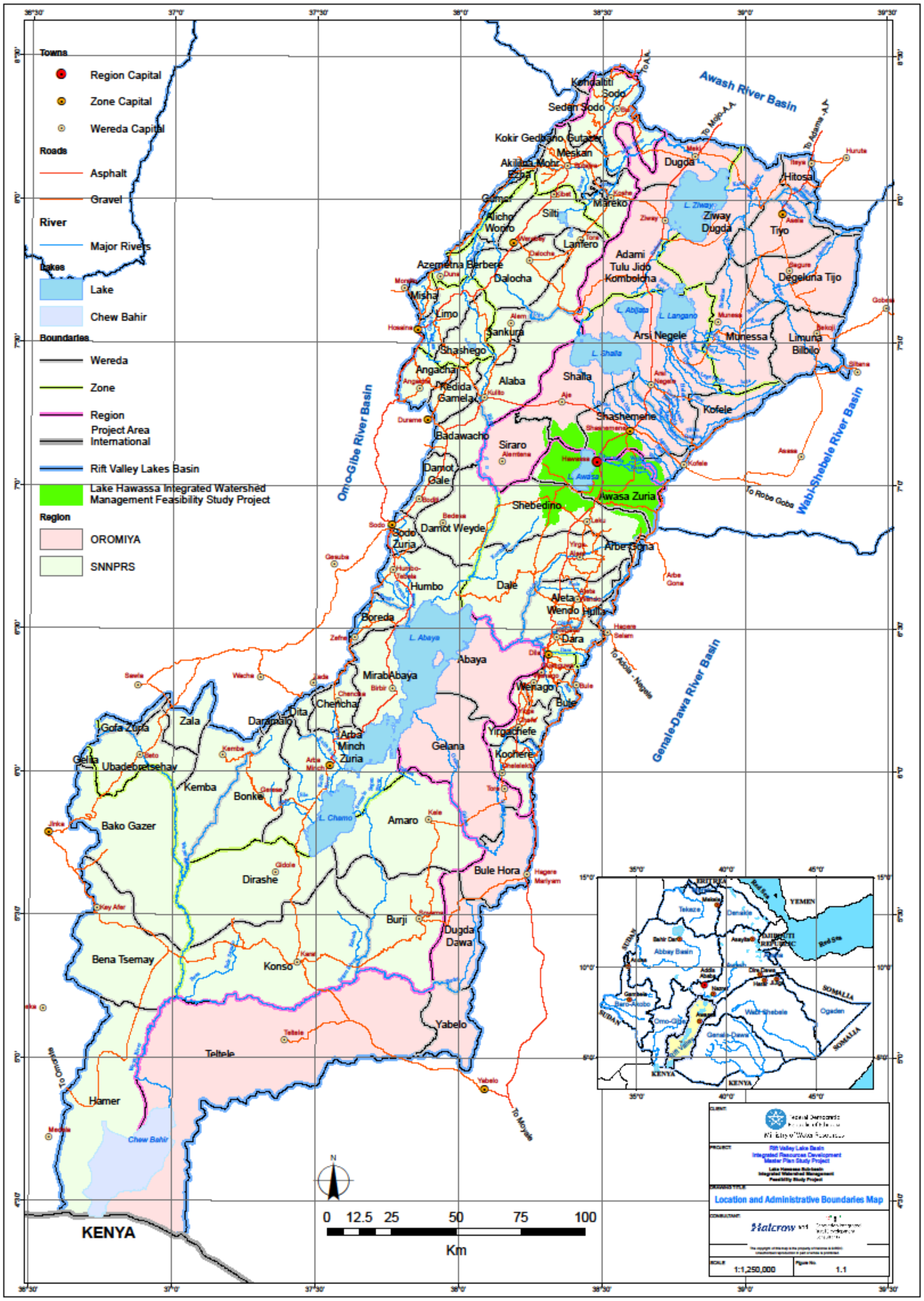


Figure 3.1. Base map of the Ethiopian Rift Valley basin [Source: MoWR, 2010)]

Table 3.1 and *3.4* depict the morphological characteristics of individual lakes in the Rift Valley Basin as compiled from different sources. The water quality parameters are also presented in *table 3.2.*

Table 3.1. Morphological characteristics of Rift Valley lakes

		Altitude (m.a.s.l)	Max. depth (m)	Mean depth (m)	Volume (km^3)
1	Lake Ziway	1636	8.95	2.5	1.6
2	Lake Langano	1582	47.9	17	5.3
3	Lake Abiyata	1578	14.2	7.6	1.1
4	Lake Shalla	1558	266	87	36.7
5	Lake Hawassa	1680	22	11	1.34
6	Lake Abaya	1285	13.1	7.1	8.2
7	Lake Chamo	1233	13	6	3.3
8	Lake Beseka	1200			

[Sources: Wood and Talling (1988), Kebede et al. (1994), Chernet (1982), Ayenew (1998), Tessema (1998), Halcrow and partners (1989), WWDSE (2001), Deganovsky et al. (2004), and Görner et al. (2009)]

Table 3.2. Selected water quality parameters of the Rift Valley lakes

Parameter	**Ziway**	**Abiyata**	**Shalla**	**Langano**	**Hawassa**	**Abaya**	**Chamo**	**Beseka**
pH	8.37	9.60	9.80	9.04	9.00	9.07	9.48	
EC (µS/cm)	453	47,915	46,075	1,937	867	1,218	1,966	7,155
Na (mg/l)	61	7,520	6,475	390	165	234	428	
F (mg/l)	1.6	220.0	188.0	9.1	8.7	8.1	9.1	
SAR	3.0	653	267	41.5	10.2	15.7	27.0	

[Source: MoWR (2009), Ayenew (1998), Wood and Talling (1988), and Halcrow and partners (1989)

3.3.2. Available data

Table 3.3 presents the magnitudes of available water balance components for the eight Rift Valley lakes of Ethiopia and *table 3.4* shows the relative surface areas of the lakes and their watershed.

Table 3.3. Water balance components of the eight Rift Valley lakes (the units are as appeared in their respective literatures, no conversion made)

Name of the lake	Inflow				Outflow				References
	P	S_{in}	R_{un}	GW_i	E	S_{out}	A	GW_o	
1 Ziway (in 10^6 m^3)	323	656.5	48	80.5	890	184	28	14.6	Ayenew (2004)
(mm)	750	1530			1720				Deganovsky and Getahun (2004)
(mm)	753	0.692km^3	0.05km^3	100	1740			200 (net)	Vallet-Coulomb et al. (2001)
2 Langano (in x10^6 m^3)	186	212		135.4	463	46		18.9	Ayenew (2004)
3 Abiyata (in x10^6 m^3)	113	230	15	26.8	372	0	13	1.2	Ayenew (2004)
(in x10^6 m^3)	97.2	179.87		13.92	290.97	0		0	Ayalew (2003)
4 Shalla (in x10^6 m^3)	232	245	18	40	781	0			Ayenew (2004)
5 Hawassa (in x10^6 m^3)	106	83.1			132	0		58	Ayenew (2004)
(mm)	950	1440			1440	0		570	Deganovsky and Getahun (2004)
(in x10^6 m^3)	80.6	74	90		164.6	0		71	WWDSE (2001)
(in x10^6 m^3)	106	83			131	0		58	Ayenew and Gebreegiziabher (2006)
(in x10^6 m^3)	90		167		148				Gebremichael (2007)
(in x10^6 m^3)	98.9	54.9	44.44		178.93	0			Shewangizaw (2010)
(in x10^6 m^3)	90.72	88.29	91.57	3.2	166.66			71.5	WRDB (2007)
(in x10^6 m^3)	106	83.7	-		132	0		58	Gebreegiziabher (2004)
(in x10^6 m^3)	106	83.7	-		132			58	Ayenew et al. (2007)
(in x10^6 m^3)								52.5	Ayenew and Tilahun (2008)
6 Abaya (in x10^6 m^3)	556				1900				Ayenew (2004)
(in x10^6 m^3)	980	750	691		2009				Belete (2009)
(mm)	730	1080			1700				Deganovsky and Getahun (2004)
7 Chamo (in x10^6 m^3)	406				900.9				Ayenew (2004)
8 Beseka (in x10^6 m^3)	22	30		52.8	98.8				Ayenew (2004)
(in x10^6 m^3)	24.4	7.7		33.8	61.8			0.22	Belay (2009)

P=over lake precipitation; S_{in}= stream flow; R_{un}= surface runoff from the watershed; E= evaporation from the lake; S_{out}= stream outflow; A= abstraction; GW_i= ground water inflow; GW_o= ground water outflow

Table 3.4. Results of characterization based on specific watershed

	Names of the Rift Valley lakes	Surface area (km^2)	Watershed area (km^2)
1	Lake Ziway	442	7025
2	Lake Langano	241	1600
3	Lake Abiyata	176	1630
4	Lake Shalla	329	3920
5	Lake Hawassa	90	1250
6	Lake Abaya	1162	17300
7	Lake Chamo	551	2210
8	Lake Beseka	43	505

[Sources: Ayenew (2004), and Deganovsky and Getahun (2004)]

3.3.3. Methods

This chapter intended to investigate the hydrology of Main Ethiopian Rift Valley lakes by assessing their long-term water balances and their morphological characteristics. Assuming the fundamental similarity of all lakes, the review adopted two different approaches to estimate the natural responses of the lakes. These techniques of characterizing the lake level regime are suggested by Szestzay (1974) based on long-term water balances and another suggestion by Litinskaya (1973) based on morphological nature of lakes. The methods are meant to show the expected natural behavior of the lake hydrology and deviations from these are considered to be shifts from the natural state. The following sections discuss the methods in detail.

3.3.3.1. Water balance approach to characterize the lake level regimes

An earlier publication of Szesztay (1974) suggested the possibility of classifying lakes based on their water balance as shown in *figure 3.2* and *3.3*. Inflow factor (i), outflow factor (o) and aridity factor (a) are the basic criteria for characterization of the lakes. The basic equations of these factors are presented below:

1. $Inflow\ factor\ (i) = \frac{Total\ inflow\ into\ the\ lake}{Total\ input\ into\ the\ lake} = \frac{\mathbf{I}}{\mathbf{I+P}} * 100$ …………………... (*3.1*)
2. $Outflow\ factor\ (o) = \frac{Total\ outflow\ from\ the\ lake}{Total\ output\ from\ the\ lake} = \frac{\mathbf{O}}{\mathbf{O+E}} * 100$ …………......... (*3.2*)
3. $Aridity\ factor\ (a) = \frac{Evaporation}{Precipitation} = \frac{\mathbf{E}}{\mathbf{P}}$ ……………..………………..…..... (*3.3*)

A lake which belongs to one of the nine categories of *figure 3.2* and *3.3* is considered as having particular characteristics in terms of stability of the water balance and the factors controlling water level fluctuation. For instance, the quadrant *I-O* represents those lakes which are flow-dominated and equilibrium condition of their water balance are quickly followed by corresponding changes in the height and regime of the water level. The quadrant *P-E* comprises "atmosphere-controlled" lakes with self-regulating mechanism responsive to climatic changes. The quadrants *IP-E* and *I-E* are expected to accumulate short term variations of precipitation which in turn increase the imbalance during extreme dry and wet periods. The other five quadrants of the scheme (*I-OE, IP-OE, P-OE, P-O,* and *IP-O*) are conceived as representing intermediate situations between the "flow-controlled" and "climate-controlled" lakes.

3.3.3.2. Morphological approach to characterize the lake level regimes

This approach is based on the suggestion by Litinskaya (1973). In this approach, it is recommended to use the term specific watershed (ΔF) which is computed as:

Specific watershed (ΔF) = lake basin area / lake surface area ……………….. (*3.4*)

According to the approach, the lakes would be classified into three groups based on the magnitude of specific watershed that is considered as a proxy to characterize the level-regime of the lakes. Those lakes having specific watersheds less than 10 are assumed to have stable lake level regime with mean annual amplitude of fluctuation ranging from 30 to 65 cm. The other category includes those lakes having specific watersheds ranging from 10 to 50 cm. These lakes are expected to be less stable in terms of increased annual fluctuation (mean annual amplitude of water-level fluctuations rises 50 to 130 cm). The third category of lakes comprises those lakes with specific watershed exceeding 50 cm. The mean annual amplitude of lake level variability in this case increases to 110 to 210 cm.

3.4. Results and discussion

3.4.1. Classification of the lakes based on their long-term water balance

Table 3.5 presents the computational results of inflow factor, outflow factor and aridity using *equations 3.1*, *3.2*, and *3.3*. The grouping of these lakes into their respective quadrants based on their calculated particularities is also presented in *table 3.5*, *figure 3.2*, and *3.3*.

Table 3.5. Results of inflow, outflow, aridity, and the corresponding quadrants

		Inflow factor (i)	Outflow factor (o)	Aridity(a)	Without aridity factor	With aridity factor
1	Lake Ziway	69.0	22.6	2.5	I-E*	IP-E*
2	Lake Langano	65.1	12.3	2.5	IP-E*	IP-E*
3	Lake Abiyata	68.6	3.7	3.1	I-E*	I-E*
4	Lake Shalla	56.6	0.0	3.4	IP-E*	I-E*
5	Lake Hawassa	53.3	23.2**	1.5	IP-E*	IP-E*
6	Lake Abaya	59.5	0.0	2.6	IP-E*	IP-E*
7	Lake Chamo	incomplete	incomplete	2.2		
8	Lake Beseka	79.0	0.0	4.5	I-E*	I-E*

* *Interpretation: Climate controlled (with little role of inflow)*

***The value represents the ground water outflow*

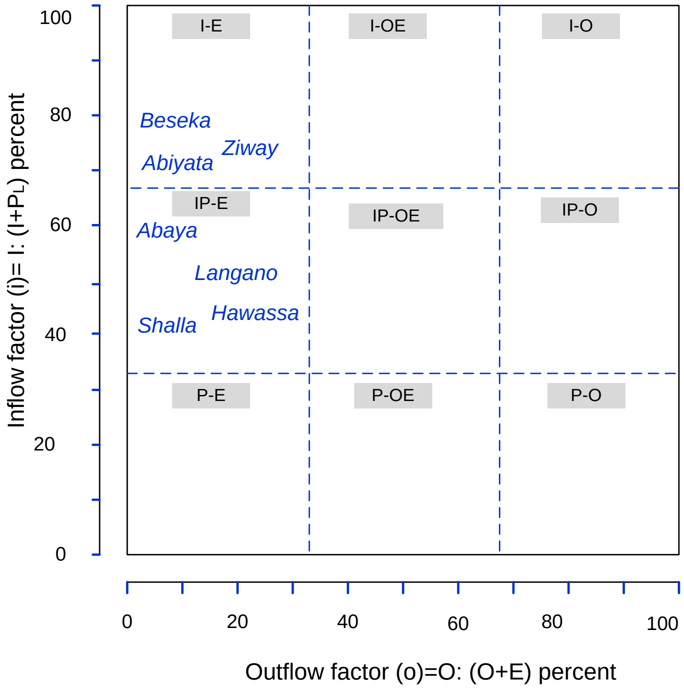


Figure 3.2. Classification of lakes by water balance criteria (aridity factor is not included)

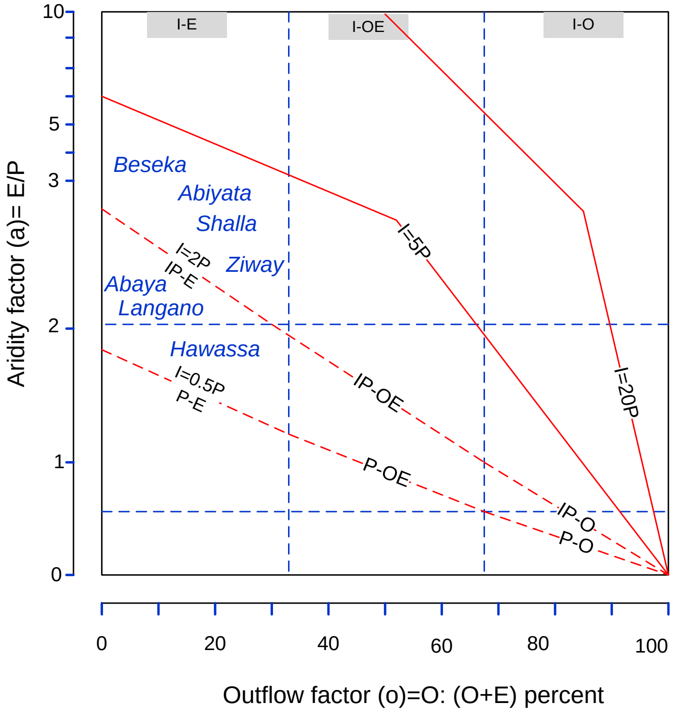


Figure 3.3. Classification of lakes by water balance criteria (aridity factor included)

The water balance analyses show that most of the lakes have similar characteristics in terms of their sensitivity to climate variability. This similarity is depicted in both cases of "with" and "without" the use of aridity factors as classification criteria. All of the lakes are under I-E or IP-E quadrant, and these two quadrants are known for their dominance in climate (with some exceptions) during extreme dry and wet periods in which runoff from the watershed increases the imbalance.

3.4.2. Classification of the lakes based on their morphology

Based on *equation 3.4*, the ratio of watershed area with lake surface area was computed and results are presented in *table 3.6* below.

Table 3.6. Results of characterization based on specific watershed

		Surface area (Km^2)	Watershed area (km^2)	Specific watershed	About level-regime	Expected mean annual amplitude (cm) **
1	Lake Ziway	442	7025	16	Moderately stable	50-130
2	Lake Langano	241	1600	6.6	stable	30-65
3	Lake Abiyata	176	1630	9.3	stable	30-65
4	Lake Shalla	329	3920	12	Moderately stable	50-130
5	Lake Hawassa	90	1250	14	Moderately stable	50-130
6	Lake Abaya	1162	17300	15	Moderately stable	50-130
7	Lake Chamo	551	2210	4	stable	30-65
8	Lake Beseka	43	505	11.7	Moderately stable	50-130

**The expected amplitudes are as suggested by Litinskaya (1973)

The result shows that lakes of mean stable level regime are dominant in the basin (Ziway, Shalla, Hawassa, and Abaya) and the rest are in the range of stable level regime (Langano, Abiyata, and Chamo) indicating the potential of the lakes to naturally regulate the surface runoff flowing into them from their watershed. This technique appears to underestimate the role of climate on Lake Hawassa as compared to the report of Tesfaye (1982) in which Lake Hawassa is found to be sensitivity to slight climatic changes.

3.4.3. Recent/actual situations of individual lake level regimes

As shown in *figure 3.4,* the long-term water level records of individual lakes. Each lake has experienced particular rise and/or drop in water levels which cannot be explained by monotonic trends (defined as the slow move up or down from the mean value and keep on moving in the same direction over time). *Table 3.7* also shows the monotonic trend of each lake under study based on raw data from literatures (for the first six lakes) and based on the results of previous studies for Lake Beseka and Lake Shalla.

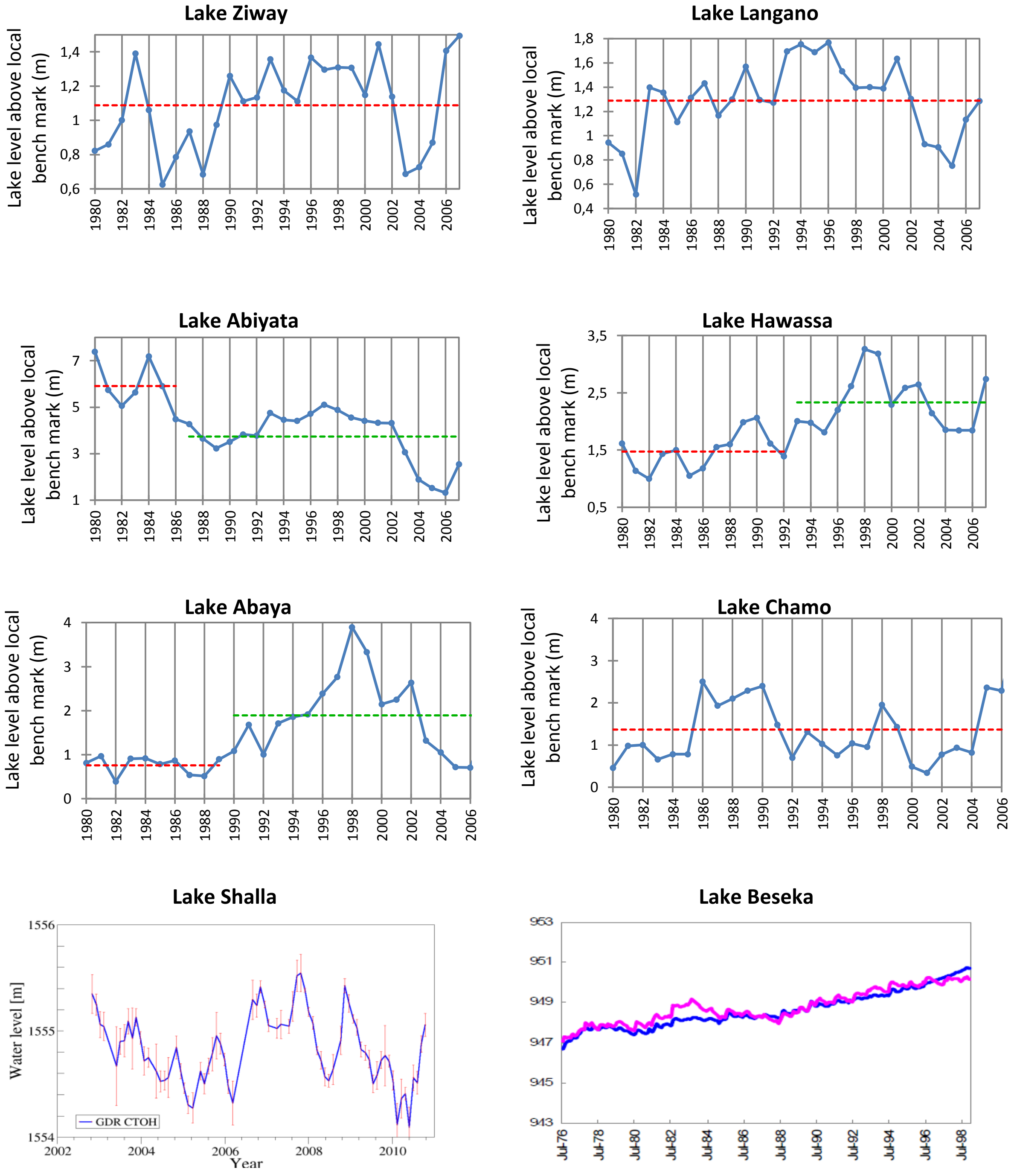


Figure 3.4. Long-term lake level plots of the eight Rift Valley lakes

***N.B**: Analysis of regime shifts were done for the first six lakes and the red lines represent mean lake level (above local bench marks) before the regime shift (μ1) and the green line after the regime (μ2).The blue bold lines for Lake Shalla and Lake Beseka represent the measured water level and the pink color for Lake Beseka, though irrelevant to this review, represents modeled lake level as reported by* Belay (2009). *(Raw data source for Lake Ziway, Langano, Abiyata, Hawassa, Abaya and Chamo is* Bewketu (2010)*; the graph for Lake Shalla is from* Crétaux et al. (2011)*; and for Lake Beseka is from* Belay (2009).

Table 3.7. Monotonic trends of level of individual lakes

		MK τ**	Interpretation
1	Lake Ziway	0.324	Increasing
2	Lake Langano	0.037	No trend
3	Lake Abiyata	-0.492	Decreasing
4	Lake Shalla	-	-
5	Lake Hawassa	0.531	Increasing
6	Lake Abaya	0.363	increasing
7	Lake Chamo	0.106	No trend
8	Lake Beseka	-	Increasing

** MK τ is the Mann-Kendall coefficient as shown in *section 4.4.5.*

3.4.3.1. Lake Ziway

The lowest level of Ziway was recorded in June 1975 (0.13 m) and the maximum in September and October 1983 (2.17 m). However, for the last three years of the late 1970s and early 1980s, the level was slightly lower due to the dry years of the 1970s. The lake shows a slight reduction after the late 1980s due to the abstraction of water for irrigation (Legesse and Ayenew, 2006; Vilalta, 2010). The existence of land degradation in the watershed that induced large scale sedimentation rate was reported by Legesse and Ayenew (2006) and Billi and Dramis (2003).

3.4.3.2. Lake Langano

Lake Langano experienced only small seasonal water level variations of about 1 m, and lower inter-annual water level variations compared to other lakes in the basin (Vilalta, 2010; Ayenew, 2001). The absence of considerable water abstraction and large ground water flow from springs are considered to be the factors against its relative stability of lake level variability. Lake-bed sedimentation is also estimated to the magnitude of about 0.5 to 0.6 cm/yr, with 85-95% water content (Legesse and Ayenew, 2006).

3.4.3.3. Lake Abiyata

Lake Abiyata is a saline-alkaline type (Wood and Talling, 1988) and in terms of lake level variability, it has experienced a drop of about five meters over the last three decades (Alemayehu et al., 2006) and also found to be heavily impacted by human activities (Alemayehu et al., 2007; Vilalta, 2010). Its size, for instance, was decreased by 25% over the last thirty years because the lake water is under pressure due to the production of Soda Ash using solar evaporation of brines from the lake and the maximum drop coincides with the time of large scale water abstraction (Legesse and Ayenew, 2006). But the inter-annual fluctuations are controlled by climate variability. According to Legesse et al. (2004), this lake also reacts more rapidly to an abrupt shift to wetter conditions than to dry conditions. The production of Soda Ash has not taken place for the last three years of the reporting time because of the significant decline in the water level (MoWR, 2008). The fluctuation of Abiyata follows the same trend as Lake Ziway, with an average time lag of about 20 days. Any abstraction of water in the Ziway watershed results in a greater reduction in the level of Abiyata than in Ziway (Legesse and Ayenew, 2006).

3.4.3.4. Lake Hawassa

The monthly and annual Hawassa lake level and Tikur Wuha stream flow showed an increasing overall trend (Wagesho et al., 2012). The possible causes of the water-level rise of the lake is associated to climate changes (Lamb et al., 2002; Ayenew, 2006; Deganovsky et al., 2008; Gebreegziabher, 2004; WWDSE, 2001; MoWR, 2008; and Bewketu, 2010); the upset of hydrological variables (Lamb et al., 2002; Gebreegziabher, 2004; Ayenew, 2004; MoWR, 2008; and Bewketu, 2010); sedimentation process (Esayas, 2010; Gebreegziabher, 2004; and Geremew, 2000) and geological tectonic processes that affect the ground water flow towards the lake (Ayenew, 2006 and WWDSE, 2001).

3.4.3.5. Lake Abaya

Lake Abaya experienced the rise of about 3.35m between 1987-1998 (12 years) followed by continuous drop of 3.12m in the years 1998-2006 and then rose by 0.91m between 2006 and 2007. While discussing these variations, Belete (2009) stated that these fluctuations are mainly caused by precipitation as input and evaporation as output and limited role of deforestation and agricultural expansion in the watershed. Even though the role is limited, the watershed experienced an expansion of agricultural lands by close to 200% in the year 2000, while bush land increased by 17% during the same period, which can be explained by continuous deforestation for agriculture and charcoal production for commercial and community use. *Table 3.8* below shows the land use/cover changes in the watershed.

Table 3.8. Land use/cover changes in Lake Abaya watershed

Land use/Land cover	In the year 1986 (ha)	In the year 2000 (ha)	Changes in percent
Bush land	50459.8	59442.4	17.8
Wet land	31512.7	20790.8	-34
Forest	180832	143195	-20.8
Agriculture	24506.7	72254.3	194.84
Water	137734	137320	-0.3
Grassland	17150.2	9192.48	-46.4

[Source: Belete (2009)]

3.4.3.6. Lake Chamo

This lake rose in the years 1989, 2006 and 2007 only and the El Niño event in 1997/1998 which caused heavy rainfall and runoff in southern Ethiopia didn't cause substantial lake level rise (Awulachew, 2006) in contrast to many other Rift Valley lakes.

3.4.3.7. Lake Shalla

Regarding Lake Shalla, the available literature is very limited. That might be due to the little interest on the lake water because of its alkaline nature (Vilalta, 2010) which discourages its use for irrigation purpose.

3.4.3.8. Lake Beseka

Despite small inter-annual variations, the water level of Lake Beseka has been rising for more than three decades which is evidenced by the quadrupled expansion of its surface area from 11.1 km^2 to 39.5 km^2 between 1973 and 2002 with the corresponding rise in lake level (Görner et al., 2009). The main cause for this expansion in surface area and rise in lake level is the increased ground water flow from the western part of the watershed. The discharges to the lake in the form of hot springs constitute the major water inflow to the lake (Görner et al., 2009; Belay, 2009; Williams, 1981; and Ayenew, 2004). It is estimated to be 51% of the total inflow to the lake (Belay, 2009). Some investigators relate the phenomena to neotectonism (Ayenew, 1998; Tessema, 1998). The average annual increment of the lake was 0.2m and the level of the lake has risen by four meters between 1976 and 1997 (Zemedeagegneh and Egizabher, 2004). Due to the expansion and flooding, the loss of 57 human lives, inundation of about 35 km^2 of grazing land, and displacement of 910 people was reported. The Methara sugar plantation has also been inundated and the company lost income from 161.55 ha of land (WWDSE, 1999). Damages on the nearby railway line and highway caused a loss amounting to 2.6 million US$ (Tessema, 1998; Ayenew, 2004).

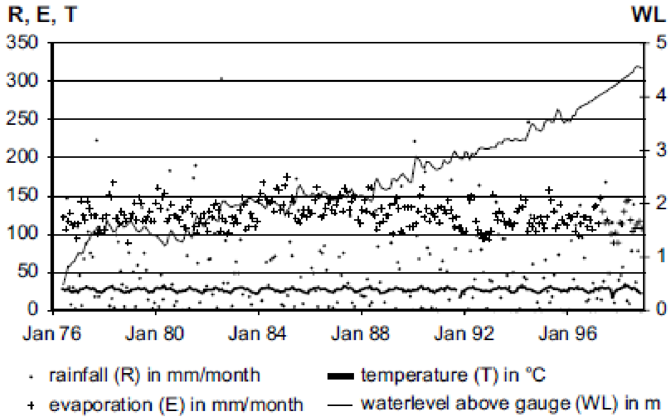


Figure 3.5. Lake level rise of Lake Beseka in relation to climatic factors (temperature, precipitation, evaporation) [Source: Görner et al., 2009]

3.5. Conclusions

The results of this chapter suggest that the hydrological statuses of most Ethiopian Rift Valley lakes are not stable in terms of their lake level variability. Few of them such as Lake Abiyata tend to be at the verge of extinction as was observed from its drastic and continuous drop in level.

In the previous section in which each lake in the Rift Valley was separately assessed, one can observe the similarity among the lakes, for instance, Lake Abaya and Lake Hawassa experienced lake level peaks in the year of 1998/99 and both of the peaks were caused by short term climatic variability. The analyses and syntheses of this review showed that long-term monotonic changes provide limited information in explaining the dynamics of lake levels. The lake level changes seem to be explained better with the consideration of specific periods and the corresponding events. In addition, the extent of the problem is not the same on each lake and each lake suffers from diverse factors and deserves individual and separate analyses. In terms of research gap identification, it was found that there existed nearly no attempt to estimate the impact of sedimentation on the storage capacity of the lakes. The explicit attempt to study the relationship between Lake Hydrology and climate anomalies is also absent. The upcoming thesis work benefits from the above research gaps. This thesis is focused on assessing the causal links of water level dynamics of Lake Hawassa, where there is a clear research gap observed.

Chapter 4. The impact of climate shifts and ENSO phenomena on the hydrological status of Lake Hawassa

4.1. Introduction

The significant rising trend of Lake Hawassa water level (as shown in *section 4.5.2.1*) is one of the main environmental threats for the city of Hawassa, which has been established at the eastern shore of the lake. It is still the subject of concern and center of debate among the stakeholders since the last few decades especially in the aftermath of the 1998 flood that caused displacement of resident population, destruction of properties and infrastructure by inundating vast areas along the lake shore. According to WRDB (2007) and WWDSE (2001), the lake level rise and the associated surface expansion affected about 162 urban and 2244 farmers' households, 13 different organizations, water supply schemes, 10 ha of sand quarry, roads, and forestland. In monetary terms, the total physical damage was estimated to be 43,490,524 Ethiopian birr (about € 5.4 million).

The hypothesis of "climate-hydrology link" was conceived in this study after the recognition of coincidence between the lowest lake level record in the year 1975 with a strong La Niña year and the maximum lake level in 1998 with the strongest El Niño year (please compare *figure 4.4* and *appendix 1*). La Niña and El Niño are anomalies in ocean surface water temperature. They are commonly termed as "teleconnections" (Wallace and Gutzler, 1981). There are reports of coherence between lake levels and teleconnection signals. For instance, Namdar-Ghanbari and Bravo (2008) reported the significant coherence between Great Lake water levels and some teleconnection signals.

One of the questions to be answered in this study is whether there is a quantifiable coherence between ENSO signals and water level variability of Lake Hawassa. Appropriate pairs of monthly step time series data were undergone through spectral analysis for the explicit estimation of "coherency" between these series. The Niño-3.4 index (N3.4), which is the average SST anomaly within the region 5°S-5°N, 170°-120°W is used as a representative index for ENSO phenomena. This index is usually employed to predict rainfall in Ethiopia (Korecha and Barnston, 2007; Babu, 2009). It is one of the most widely used ENSO index (Barnston et al., 1997).

The use of spectral coherence analysis is quite recent in the area of hydrology. The coherence analysis in this study was made following the idea of Jenkins and Watts (1968) and

Bloomfield (1976). This technique is employed to quantify analyze the relationship between Niño 3.4 index and lake level data series. The significance of coherence resulting from this technique suggests that changes in one series is related to changes in the other.

In addition to coherence analysis, the coincidences of significant regime shifts in lake level, streamflow, and lake-evaporation with climate shifts and timing/intensity of ENSO phenomena were investigated to further strengthen the result of coherence analysis towards a better understanding of climate-hydrology link.

The concept of "regime" in hydrology tells us the temporal pattern of the variable under discussion over a period of time and "regime shift" was originally proposed in relation to oceanic ecosystem (Steele, 1996; Hare and Mantua, 2000) to describe sudden drastic changes in temporal characteristics of a variable (Yang et al., 2012). The definition of climatic regime shifts can be viewed as "differing average climatic levels over a multi-annual duration" (Overland et al., 2006). Shifts in the mean are the most common type of shifts considered in literature (Rodionov, 2004; 2005). The main driving forces of variability in hydrological variables are climate change and human activities (Zhao et al., 2009; Xu, 2011).

Improved understanding of the effects of climate variability on the water level of Lake Hawassa can help in managing the hydrosystem in general. According to Lenters et al. (2005), the changes in water level reflect alteration of water balance components. So, the explicit analysis of hydro-climatic variables together with their linkage with climate anomalies would provide a better insight into the inherent variability of hydrological status of the lake.

4.2. Hypothesis and objectives of the chapter

The sort of hypothesis to be proved in this chapter is stated as:

> "*The water level variability of Lake Hawassa is linked to Sea Surface Temperature (SST) anomalies. It is further studied, whether regime shifts occur in the hydro-climatic variables corresponding to the occurrence of North Pacific climate shifts and El Niño/La Niña events*".

In line with the hypothesis, the objectives of this chapter are:

- To analyze the coherence between data series of Niño 3.4 Index (N3.4) and Lake Hawassa water level;
- To analyze the long-term trends (variation over-time) and sequential regime shifts (variation across-time) for lake level, rainfall, streamflow, and lake-evaporation data series; and
- To compare significant change points of the above hydro-climatic variables with the timing and intensity of North Pacific climate shifts/El Niño/La Niña occurences.

4.3. Impact of El Niño/La Niña on climate variability of East Africa

National Oceanic and Atmospheric Administration - NOAA's (www.nws.noaa.gov) and many other websites provide the detailed characteristics, impacts, intensities and answers to frequently asked questions about El Niño/La Niña events. So any interested reader can refer these sources. According to these sites, El Niño represents the warm phase of the El Niño/Southern Oscillation (ENSO) cycle and La Niña represents the cool phase of the cycle, and is sometimes referred to as a Pacific cold episode.

The El Niño-Southern Oscillation (ENSO) phenomena have a strong impact on the weather and climate variability of Ethiopia (Haile, 1988). Farther to the north, Eastern Equatorial Africa-a region that includes Kenya, Southern Ethiopia, Somalia, Uganda, and Tanzania - generally experiences more rainfall during El Niño years. There, the deluge associated with the 1997 El Niño was nearly unprecedented (Ropelewski, 1999). Similarly, Goddard and Graham (1999) commented that the rainfall variability in Eastern and Southern Africa is the conjunction of two competing effects of the Pacific and the Indian Oceans. Warming of the Eastern Tropical Pacific, during an ENSO event, tends to alter the atmospheric circulation dynamics above Eastern Africa and to reduce rainfall rate on this area. The effects of La Niña are generally less pronounced in Eastern Equatorial Africa and tend to be the opposite of those of El Niño (Nicholson and Selato, 2000). The interval between the two strongest El Niño events occurred only 15 years apart and it should be typically 30 to 40 years and these changes are unlikely to be due to natural variability alone (Trenberth and Hoar, 1997), and natural atmospheric cycles such as the Pacific Decadal Oscillation (PDO), the Madden-Julian

Oscillation (MJO) or the chaotic nature of the atmosphere might also have a role to play (McPhaden, 1999).

The Oceanic Niño Index (ONI) has become the de-facto standard that NOAA uses for identifying El Niño (warm) and La Niña (cool) events in the tropical Pacific. For the purpose of reporting, for an event to be categorized as weak, moderate or strong it must have equaled or exceeded the threshold for at least three months. The threshold is broken down into Weak (with a 0.5 to 0.9 SST anomaly), Moderate (1.0 to 1.4) and Strong (≥ 1.5) events (Null, 2013).

4.4. Methods

4.4.1. Data availability

As shown in *table 4.1*, there exists fairly long sequence of hydro-climatic data for Hawassa meteorological station which is the nearest station for the lake under consideration. Other meteorological stations in the watershed (refer *figure 2.4* in *chapter two*) have limited data. Data gaps are filled by linear interpolation throughout the study.

Table 4.1. The core set of hydro-climatic data employed in the study

Data type	Temporal scale	Period	Sources
Lake level records	Daily	1970-2010	Ministry of Water Resources
Stream flow	»	1980-2006	»
Rainfall for:			
• Hawassa	Daily	1972-2010	Meteorological Agency
• Wendo Genet	Monthly	1974-2010	»
• Shashemene	»	1974-2010	»
• Yirbaduwancho	»	1974-2010	»
• Haisawita	»	1974-2010	»
Pan-evaporation	Daily	1986-2007	»
Wind speed	»	1989-2010	»
Relative humidity	»	1985-2010	»
Temperature	»	1973-2010	»
Sun-shine hours	»	1985-2010	»

4.4.2. Estimation of coherence between ENSO index and lake level variability

Time series data records of any two continuous variables suitable for computing a covariance, if of sufficient length for computing a stable fast Fourier transform (fft), can be transformed into the frequency domain for computation of a dimensionless squared spectral coherence (Biltoft and Eric, 2009). Transforming from the time to the frequency domain and computing the squared spectral coherence (CH) provides frequency-stratified results that can be tested for statistical significance using the F distribution (Biltoft and Eric, 2009). Frequency is defined as the number of cycles per unit time. Coherence, also known as coherency spectrum, is a widely used measure for characterizing linear dependence between two time series. Classical books on time series analysis present coherence as "the frequency domain analogue of the autocorrelation function" (Hernando and Bellegem, 2006). Further information on spectrum analysis can be referred from books such as Koopmans (1974) and Bendant and Piersol (1986).

The presence of trend in a time series data produces a spectral peak at zero frequency, and this peak can dominate the spectrum in that other important features are obscured (GEOS, 2013). Due to this, detrending should be part of the analysis. In this study, the time series were detrended using linear regression (that means: the difference between the expected value computed from a linear regression through the series and the data point is added to the mean of the series). The autocorrelations in the time series were also removed by differencing techniques with order 1.

According to the coherence analysis that is used in this study (Von Storch and Zwiers, 1999; Jenkins and Watts, 1968; and Bloomfield,1976):

The cross-spectrum (coherence analysis) is defined from the covariance function C_{xy}:

$$\Gamma_{xy}(\omega) = \sum_{\tau=-\infty}^{\infty} C_{xy} exp\{-2\pi i\tau\omega\}, \omega \epsilon\left[-{}^{1}/_{2}, \ldots, {}^{1}/_{2}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

This is a complex function where the power is:

$$A_{xy}(\omega)^2 = Re(\Gamma_{xy}(\omega))^2 + \mathrm{lm}(\Gamma_{xy}(\omega))^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

and the phase is:

$$\Phi_{xy}(\omega)=tan^{-1}\left(\frac{\mathrm{lm}((\Gamma_{xy}(\omega))}{Re(\Gamma_{xy}(\omega))}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.3)$$

A cross-spectrum for two similar processes, but with one shifted in time with respect to the other (x(t) and x(t + τ)), gives the same power spectrum as for the same analysis applied to two identical time series, x(t) but instead of a phase difference of zero, the phase is linear in frequency with a slope proportional to the phase shift: $\Phi xy(x) = 2\pi\tau\omega$.

The coherence spectrum is analogous to the conventional correlation coefficient and is defined as:

$$K_{xy}(\omega) = \frac{A_{xy}(\omega)^2}{\Gamma_{xx}(\omega)\Gamma_{yy}(\omega)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.4)$$

Namdar-Ghanbari et al. (2009) employed similar analysis to examine the relationships between ice, local climate and the teleconnections, Southern Ocean Oscillation (SOI), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), and Northern Pacific Index (NP).

4.4.3. Significance limits of the spectral coherence estimation

As noted by Thomson and Emery (2001), the final step in any coherence analysis is to specify the confidence limits (i.e. the level up to which the coherence-square values can occur by chance) for the coherence-square estimates. This step places the spectral results in a complete statistical context.

It is noted that each Fourier frequency is associated with only two degrees of freedom (Thomson and Emery, 2001) regardless of length of the records. In this spectral analysis, there exist 492 data points (pairs of monthly records) in the time series and the band width is computed as 1/492=0.002 cycle/month (*Band width is the width of the frequency interval applicable to a spectral estimate* (GEOS, 2013)). The 492 observations have 256 points in the spectrum and each of these 256 (half of the total observation) spectral estimates would have two degree of freedom. However, results based on two degrees of freedom are not statistically reliable (Thomson and Emery, 2001) or unlikely to be reproducible (Hartmann, 2013). Hence, some sort of ensemble averaging or smoothing of spectral estimates is required. As noted by Engle (1976), the width of the window is an important parameter in the estimation. The wider the window, the smaller is the variance of the resulting estimate. The wider the window, the more serious may be the bias of smoothing over non-smooth portions of the spectrum. The more smoothing we do, the narrower the confidence limits and the greater the reliability of any observed spectral peaks. The trade-off is loss of spectral resolution and longer processing time. The windowing approach, which partitions the time series into a series of shorter overlapping segments, is one of the computation methods used to smooth (average) spectral estimates (Thomson and Emery, 2001).

According to Engle (1976), the spectral estimator resulting from smoothing the periodogram is approximately proportional to another chi squared random variable, this time with more degrees of freedom. The equivalent degrees of freedom (EDF) are equal to:

$$EDF=B * m \quad \text{………………………………………..…………} \quad (4.5)$$

where B is band width and m is the number of observations.

Considering the recommendation of Engle (1976) in that the sensible value of windows span (the author used the term "range" in the paper) is the square root of the number of observations. Span of 23 was used in this study. "Range" is defined as the number of spectral points used in each moving average. It gives the separation between which two points are known to be completely independent.

As a method to increase the degree of freedom, smoothing of the data series using Daniell´s window with span of 23 was used and the degree of freedom was increased to 46 (which is assumed to be against the resolution of the spectrum). "Resolution" is the ability of the spectrum to represent the fine structure of the frequency properties of the series (GEOS, 2013). The new bandwidth of this spectrum now becomes 46/492=0.093 cycle/month. Smoothing the spectrum means that we have fewer independent estimates but greater statistical confidence in the estimate we retain. The number of degrees of freedom for each spectral estimate is just twice the number of realizations of the spectrum that we average together (Hartmann, 2013). Biltoft and Eric (2009) conformed that the best solution will likely include equivalent degrees of freedom in the midrange between 10 and 100. The F test results with degrees of freedom that fall within the middle of this range produce the most consistent and reliable results. As presented by Ghanbari et al. (2009), the estimated coherencies are considered significant at the 99% and 95% level of confidence when they are larger than the critical value T derived from the upper 1% and 5% points of the F-distribution on (2, d-2) degrees of freedom:

$$T = \frac{2F}{d-2+2F} \quad \text{………………………………………………………….………} \quad (4.6)$$

where d is the degrees of freedom associated with the univariate spectrum estimates. Coherence peaks indicate frequencies at which the principal flux activity is occurring (Biltoft and Eric, 2009).

4.4.4. Sequential regime shift detection using Regime Shift Index (RSI)

A jump in a series that is detected by a regime shift test can imply changes in either climatic factors or watershed characteristics (Tu et al., 2004). According to Breaker (2007), change points occur where the changes are relatively abrupt. Formally, a change point exists at a time t_0, if all of the observations up to t_0 share a common statistical distribution, and those after t_0, share a different statistical distribution.

Rodionov (2004) introduced an algorithm for detecting sequential regime shifts in time series data in seven steps. *Figure 4.1* summarizes the seven steps of Rodionov (2004) in the form of flow chart.

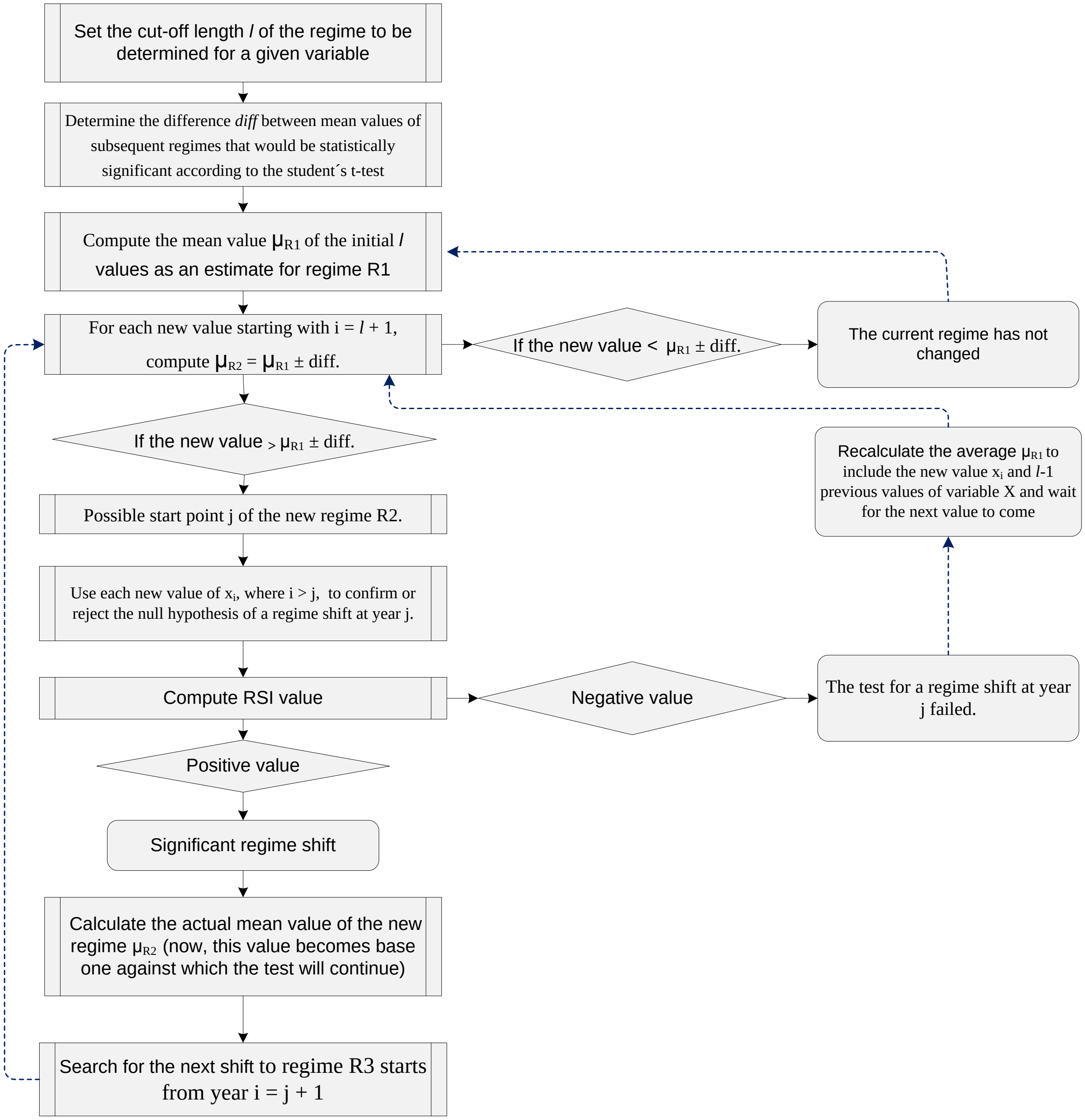


Figure 4.1. The procedure to determine sequential regime shifts [N.B: the diagram is drawn based on the seven procedural steps proposed by Rodionov, 2004]

The above procedures are automated and freely downloadable in the form of an Excel Add-In at *www.BeringClimate.noaa.gov*. The latest version (Ver. 3.4) is used in this study which has additional attribute of considering the presence of auto-correlation in the datasets using the procedure as shown in *figure 4.2* below.

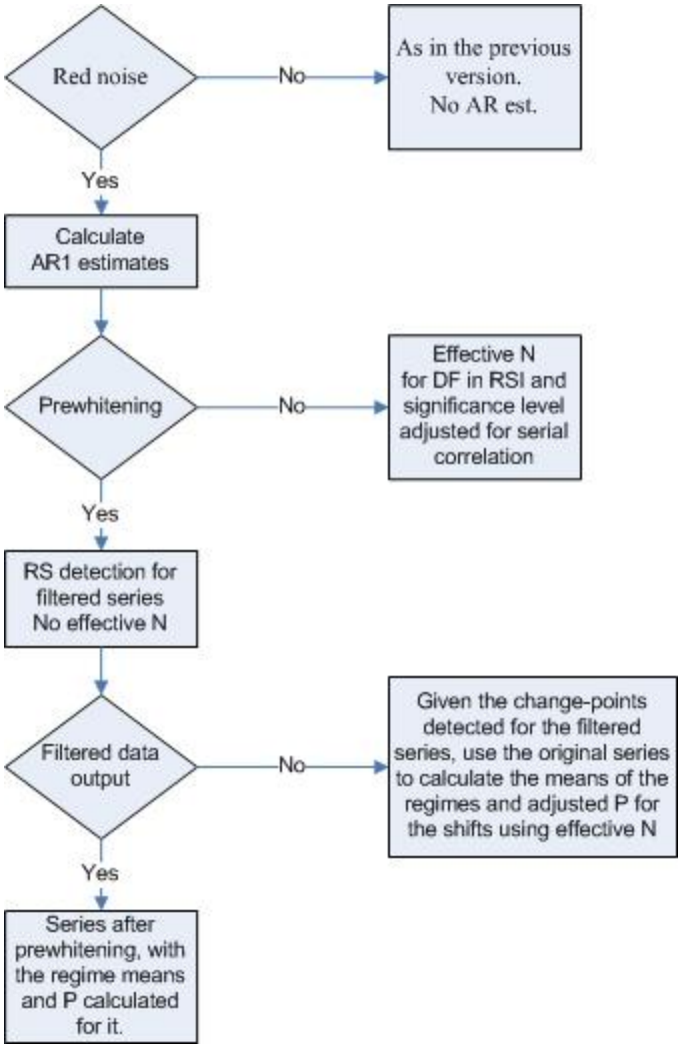


Figure 4.2. The procedure to account for the existence of autocorrelation
[Source: Rodionov, 2004: version 3.4]

4.4.5. Detection of long-terms trends using Mann-Kendall test

The statistical significance of long-term monotonic trend of Lake Hawassa water level had not been computed before, at least to our knowledge, and need to be computed. Statistical trend analysis is a hypothesis testing process. The null hypothesis (H_0) is that there is no trend. Each test has its own parameters for accepting or rejecting H_0. Failure to reject H_0 does not prove that there is no a trend, but indicates that the evidence is not sufficient to conclude with a specified level of confidence that a trend exists (NNSMP, 2011). Trend analysis enables to detect significant variations over time. It is easily understood and communicated, and readily accepted due to its widespread use (TSOA, 1995). In this study, the Mann-Kendall (MK) statistical trend test (Mann, 1945; Kendall, 1975) was employed to investigate trends in time series data. It is a kind of non-parametric test and compares the relative magnitudes of sample data rather than the data values themselves (Gilbert, 1987 *as cited in* Tabari et al., 2011; Tabari and Marofi, 2011). It allows us to investigate long-term trends of data without assuming any particular distribution. The other advantage is its low sensitivity to abrupt breaks due to inhomogeneous time series (Jaagus, 2006 *as cited in* Tabari et al., 2011; Tabari and Marofi, 2011). In this study, the 5% level of significance was considered.

The test statistic S measures the monotonic dependence of X on t:

$$S = P - M \quad \dots\dots\dots\dots\dots\dots\dots\dots \textit{(4.7)}$$

where :

- P = # of (+), the # of times the X's increase with t, or the # of $X_i < X_j$ for all $t_i < t_j$ ("concordant pairs").
- M = # of (-), the # of times the X's decrease with t, or the number of $X_i > X_j$ for all $t_i < t_j$ ("discordant pairs").
- i = 1, 2, … (n-1); and j = (i+1), …, n.

There are n(n-1)/2 possible comparisons to be made among the n data pairs. If all y values increased along the x values, S = n (n-1)/2. In this situation, $\tau = +1$, and vice versa. Therefore, dividing S by n(n-1)/2 will give a $-1 < \tau < +1$.

$$\tau = \frac{S}{n\,(n-1)/2} \dots\dots\dots\dots\dots\dots\dots\dots \textit{(4.8)}$$

The null hypothesis in accordance with this test H_0 states that the data $(x_1, \dots, x_n)$ is a sample of n independent and identically distributed random variables. The alternative hypothesis H_1 of a two-sided test is that the distributions of x_k and x_j are not identical for all $k, j \leq n$ with $k \neq j$. The test statistic S, which has mean zero and a variance computed by *equation 4.11*, is calculated using *equation 4.9* and *4.10*, and is asymptotically normal:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \dots\dots\dots\dots\dots\dots \textit{(4.9)}$$

$$sgn(x_{j-}x_k) = \begin{Bmatrix} +1 \ if \ (x_j - x_k) > 0 \\ 0 \ \ if \ (x_j - x_k) = 0 \\ -1 \ if \ (x_j - x_k) < 0 \end{Bmatrix} \dots\dots\dots\dots\dots\dots \textit{(4.10)}$$

$$Var(S) = \frac{\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)\right]}{18} \quad \text{...} \quad (4.11)$$

where n is the number of data points, m is the number of tied groups (a tied group is a set of sample data having the same value), and t_i is the number of data points in the i_{th} group. In cases where the sample size n >10, the standard normal variable Z is computed by using *equation 4.12*.

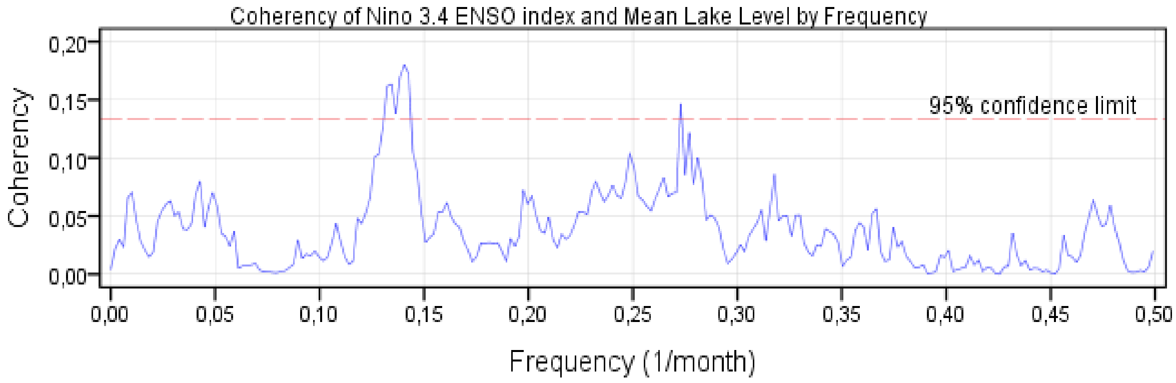
$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \; if \; S > 0 \\ 0 \; if \; S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} \; if \; S < 0 \end{cases} \quad \text{...} \quad (4.12)$$

Positive values of Z indicate increasing trends, while negative values of Z show decreasing trends. When testing either increasing or decreasing monotonic trends at α significance level, the null hypothesis is rejected for an absolute value of Z greater than $Z_{1-\alpha/2}$, obtained from the standard normal cumulative distribution tables (Partal and Kahya, 2006; Modarres and Silva, 2007 *as cited in* Tabari and Marofi, 2011). This statistical analysis is performed using xlstat2013 statistical software.

4.5. Results and discussion

4.5.1. Results of coherence analysis

Figure 4.3 shows the result of coherence analysis. The values of coherency (y-axis) versus frequency (x-axis) between the Niño 3.4 ENSO index and monthly mean lake level changes.



Summary statistics and options:

- *Type of smoothing: Daniell´s window (a simple (equal weight) moving average spectral window)*
- *Window span (width)= 23 months (which must be an odd number)*
- *Degree of freedom = 2 x 23 = 46*
- *Preprocessing: Detrending (by linear regression) and removal of autocorrelation (by differencing)*
- *Total number of paired observations in the series: 492 monthly data (implying 256 in the spectrum)*
- *Bandwidth=46/492 = 0.093 cycle/month*
- $F_{2,44}$*=5.12 (for 99% confidence limit) and* $F_{2,44}$ *=3.21 (for 95% confidence limit)*
- *Critical coherence squared @99% confidence limit =0.196 and @95%= 0.133*

Figure 4.3. Coherence between ENSO index and lake level variability in frequency domain

As evidenced by the result of coherence analysis (*figure 4.3*), the cyclic nature of Lake Hawassa water level variability has significant linear relationship to the climate variability at some frequencies. Here appear two significant peaks at 95% confidence limit. Further probe to the prominent peak reveals that the peak occurred at a frequency between 0.13-0.14 cycle/month or 1.56-1.68 cycle/year. This corresponds to a period of about 7.14-to-7.69 months (=1/0.14 -to- 1/0.13) or a dominant average periodicity (coincident cycle) of about 7.4 months. A relevant finding was reported by Namdar-Ghanbari and Bravo (2008) in which the levels of Great Lakes and Trans-Niño Index (TNI) show significant coherence in the frequency range $(3\text{-}7)^{-1}$ cycles/year.

The vital importance of the above analyses is the detection of significant coherence at some specific frequency ranges and confirmed that significant portion of the lake level variability is caused by factors operating on a scale larger than processes in the watershed. The upcoming sections attempt to further analyze the existence of regime shifts in some of hydro-climatic variables and reconcile the timing and intensities of El Niño/La Niña events with regime shift points in time domain.

4.5.2. Variability in the lake level

4.5.2.1. Long-term trend (1970-2010)

The visual inspection of *figure 4.4* (below) uncovers the underlying variability of the observed lake level by suggesting that the overall oscillation tends to be chaotic than periodic. The highest peak was observed in November 1998 (22.54 m) followed by October and December of the same year (22.49 m each). The lowest level in this year (June) (21.8 m) was greater than 92.5 % of historical records. This particular year was known for its peak records in many parts of the world. The cases of Lake Abaya (another Rift Valley lake in Ethiopia) (Belete, 2009); Lake Nasser (Egypt), Lake Chad, Lake Turkana, Lake Tanganyika, Lake Victoria, and Lake Mwero (Mercier et al., 2002) are among the few examples.

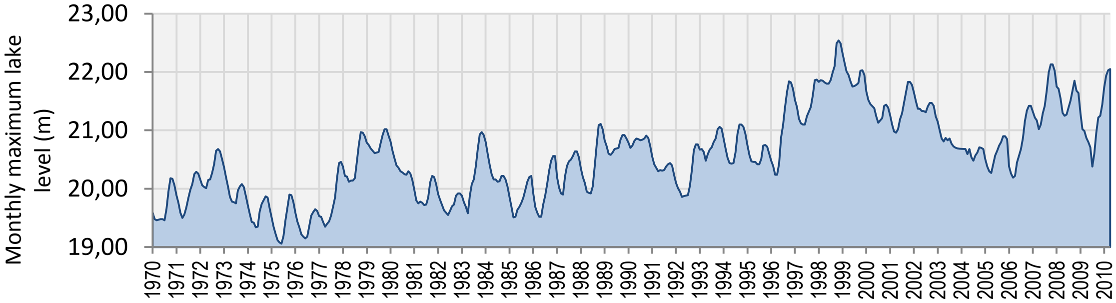


Figure 4.4. Hydrograph of monthly maximum lake level

Despite the multiple rises and falls, the lake level experienced a significant resultant upward trend with Mann-Kendall τ values of 0.558, 0.629, and 0.545 (at α= 0.05 and p <0.01%) for monthly maximum, average and minimum values respectively. The ultimate evolution of increasing trend is not gradual and consistent in direction (monotonic) rather sharp rises and falls have been frequently appearing and such variations are likely to bias the monotonic trend. Similar comment was given by Hartmann and Wendler (2005) in that the use of trend analysis in climate change research depends greatly upon the time period studied, and results can be biased when an abrupt climate change is observed during the study period.

The long-term annual average increment was also estimated to be 4.9 cm/yr (as computed by regression equation) which is low as compared to Lake Beseka (another lake located in the same basin), which has average annual increment of 20 cm (Zemedeagegneh and Egizabher, 2004).

Regarding the connection of ENSO events to the extreme values of observed lake levels, the 1998 record (historical maximum) can easily be justified for its connection to the worst El Niño event of the twentieth century (Tereshchenko et al., 2002, Magaña et al., 1999, and Strub and James, 2002) as measured by changes in the Pacific (Marucci, 2002). Globally, this El Niño year caused loss of approximately 35-45 billion USD (Sponberg, 1999). On the contrary, the lowest lake level was observed in 1975 which is likely linked to the two consecutive strong La Niña events of 1973-74 (the strongest in the period 1950-2012) and 1975-76 (*appendix 1*).

4.5.2.2. Sequential regime shifts in the lake water level

Figure 4.5 (a, b and c) and *appendix 2* demonstrate that the observed annual average, maximum, and minimum lake levels have undergone a couple of regime shifts reflecting the instability of the hydro-system.

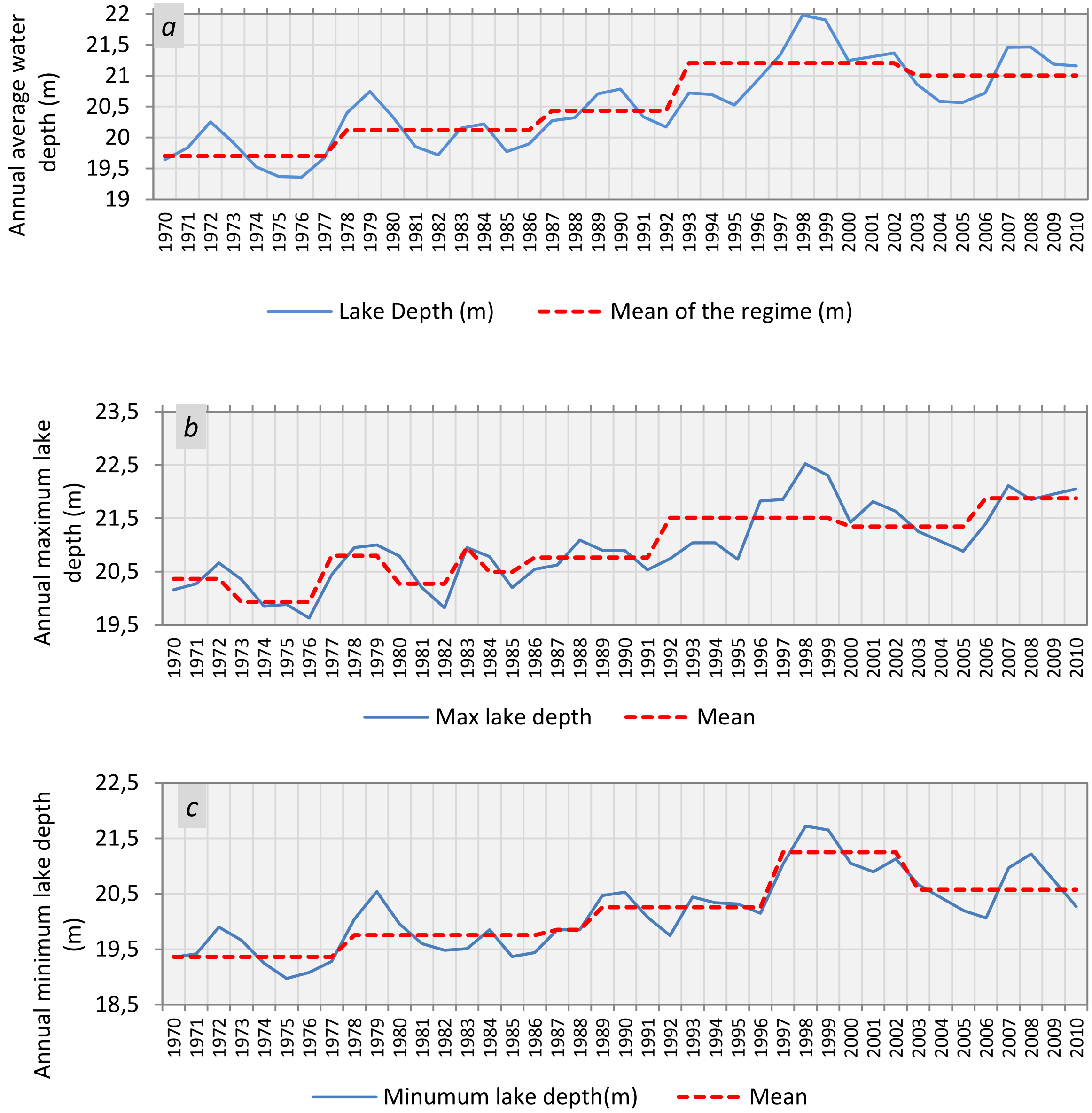


Figure 4.5. Sequential regime-shifts in annual lake levels (a) average, (b) maximum and (c) minimum

The important aspect of the prevailing regime shifts lies on their occurrence in the year 1976-78 (*figure 4.5: a,b,c*) which was known for the climatic regime shift period of the North Pacific (Miller et al., 1994, and Yletyinen et al., 2012). The year 1977 also experienced the highest historical recorded annual total rainfall (1226 mm) (*appendix 3*). The maximum lake level has undergone a regime shift in 1983 (*figure 4.5: b*) which is likely associated to the devastating El Niño of 1983. The other smaller shift in mean value of lake level occurred in 1986 which was likely caused by moderate but prolonged El Niño of 1986-87. Another connection that is manifested by the overlap of regime shift of Lake Hawassa water level and the North Pacific climate regime shift was observed in 1989 (*figure 4.5: c*) and Yletyinen et al. (2012) reported that in 1989, a new regime shift (in the climate of the Pacific) had also occurred but the changes were not as remarkable or pervasive as in the 1976-77.

The highest regime shift was observed in 1992 which showed an upward shift in mean value of the lake level from 20.43 m to 21.2 m (*appendix 2)*, implying a regime shift of 0.77 m. This regime was extended up to 2002 and known for its frequent El Niño years of 1991-92 (strong), 1994-95 (moderate), and the 1997-98 El Niño (strong). Swanson and Tsonis (2009) also noted that climate shifts occurred around 2001/2002 too and Lake Hawassa also experienced water level regime shift in this year. The relatively sustained maximum lake level regime extended from 1992 up to 1999 (*figure 4.5: b*) signifies the occurrences of three El Niños (strong, moderate, strong consecutively) without the occurrence of La Niña in between (*appendix 1*).

The general upward shifts between 1978 and 1998 are in agreement with the work of Peterson and Schwing (2003). They identified the PDO index to be negative for most years during 1948-1976 and positive during 1977-1998. In addition, Niebauer (1998) observed that before the regime shift, the occurrence of El Niño and La Niña conditions was about even. Since the regime shift, El Niño conditions are about 3 times more prevalent and this further signifies the effect of climate.

4.5.3. Rainfall variability in the watershed

4.5.3.1. Hawassa meteorological station as representing the over-lake precipitation

Figure 4.6 and *appendix 3* show the sequential regime shifts in annual rainfall at Hawassa meteorological station that represents the over-lake rainfall (refer *figure 2.4*). According to the figure, the rainfall time series shows high variability with nine distinct regimes over the study period. The relatively long and stable regime extended from 1986-to-1994 (upward shift) followed by regimes of 1999-2004 (downward) and 2005-2010 (upward). The remaining regimes are short lived and most of the breaking points coincided with the occurrences of ENSO phenomena (1976, 1983, and 1994). The climate regime shift of North Pacific Ocean that occurred in 1976/77 seems to manifest itself by causing an upward shift in both years. The annual total rainfall record of 1977 was the highest of the records (1226 mm). The shift in

1998 was also most likely linked to the transition from strong El Niño (97-98) to the two consecutive strong La Niñas (98-99 and 99-00).

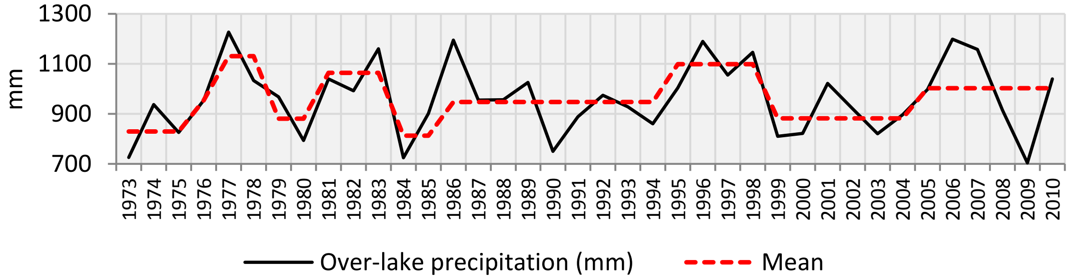


Figure 4.6. Regime shift of over-lake rainfall

The monotonic trend analysis on this rainfall data shows no significant trend throughout the recorded time span (both monthly and annual scale). The markedly uniform inter-annual fluctuations of rainfall in East Africa were also reported by Nicholson (1996). The author also showed the strong links between rainfall fluctuations and ENSO phenomena.

4.5.3.2. Rainfall at the other stations

As shown in *figure 4.7*, the years 1986 and 1987 are the common breaking points for the upward shift for Wendo Genet. The year 1982 (strong El Niño) likely caused the shift in the rainfall of Wendo Genet and Shashemene. Because of the presences of wide data gaps, the data from these stations are less reliable and may only serve as a support to the other analyses. Rainfall data at Yirbaduwancho and Haisawita stations are not included in this analysis due to similar reason.

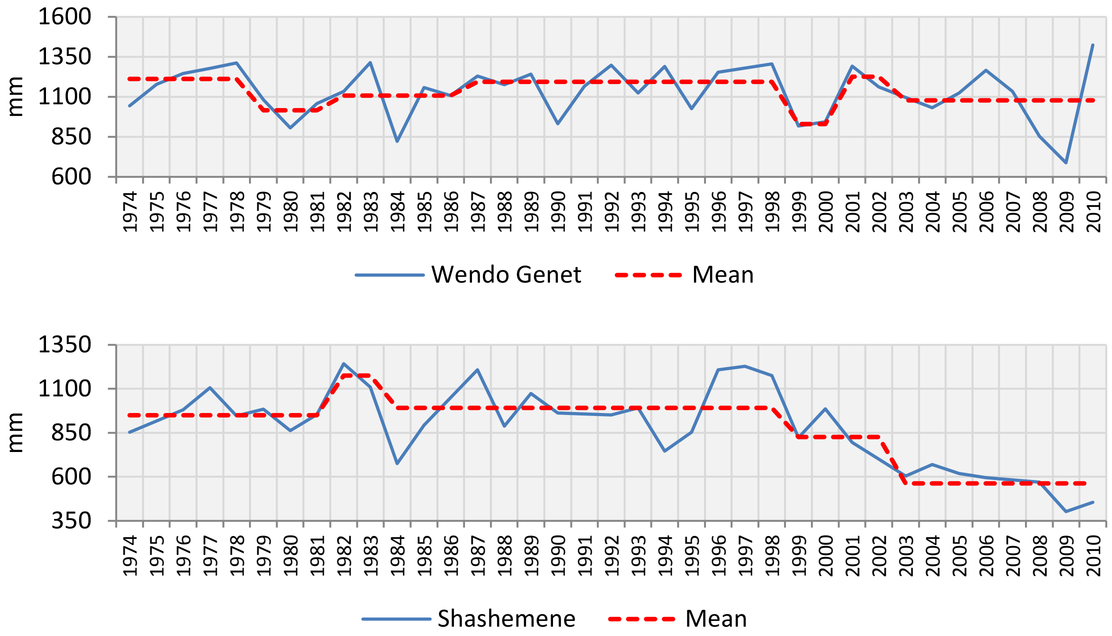


Figure 4.7. Sequential regime shifts in the annual rainfall on the watershed

4.5.4. Variability in the streamflow of Tikur Wuha River

4.5.4.1. Long-term trend

The trend analysis result of Tikur Wuha streamflow (the only perennial river flowing into the lake) shows a significant increasing trend (MK τ=0.66 for the annual average and 0.385, 0.662 and 0.508 for the three local seasons of June-Sep (Kiremt), Oct-Feb (Baga) and March-May (Belg) respectively. Monthly values also show similar trend (MK τ=0.440 at p <0.01%).

The increasing trend of the stream flow without the corresponding trend in rainfall indicates the modification of the hydro-system (Chang, 2007). This argument is discussed in *section 4.5.6.*

4.5.4.2. Detection of regime shifts

Figure 4.8 and *appendix 4* demonstrate the variability of streamflow of Tikur Wuha across time. The first breaking point occurred at 1986 which is known for its moderate El Niño. As shown in the previous section, rainfall records at Hawassa and Wendo Genet experienced similar upward shifts implying that the rainfall was the likely cause of the shift. The years 1994 and 1997 are also another change points corresponding to the timing of ENSO events.

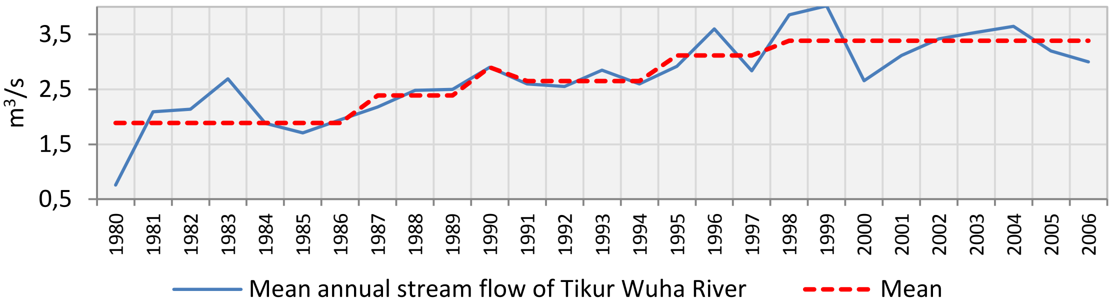


Figure 4.8. Regime shift in Tikur Wuha stream flow

4.5.5. Shift detection in the runoff coefficient of Tikur Wuha sub-watershed

Tikur Wuha River is the only stream that has been gauged in the watershed and the time series data of this river was used to analyze the regime shifts in runoff coefficient values. The runoff coefficient is the ratio of total streamflow volume to the total precipitation over a certain area and time (Kadioglu and Sen, 2001). Four meteorological stations are found in and around Tikur Wuha sub-watershed as shown in *figure 4.9*.

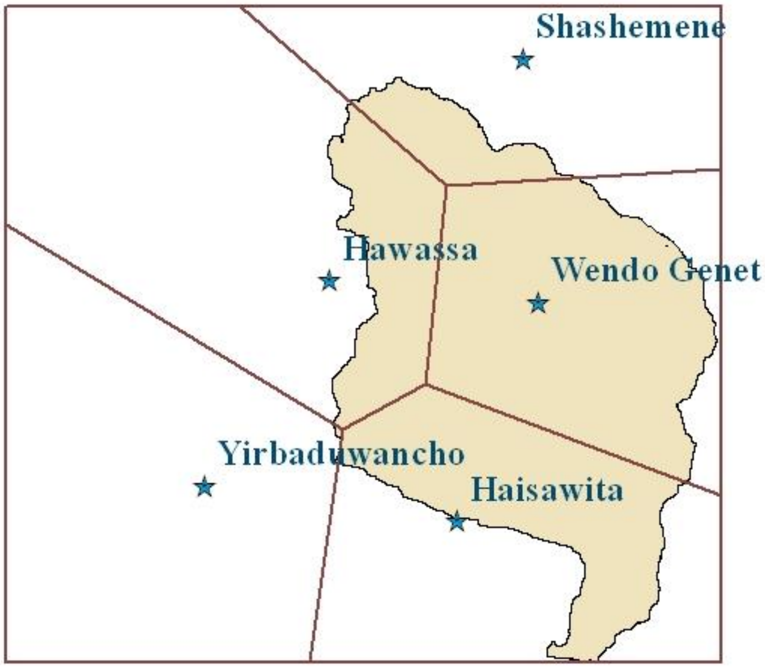


Figure 4.9. Tikur Wuha sub-watershed and Thiessen polygon

The percentage contribution of each station to Tikur Wuha sub-watershed is: Hawassa (24%), Wendo Genet (38%), Haisawita (27%) and Shashemene (11%). As presented in *table 4.2*, the annual runoff coefficient (C) for Tikur Wuha River is computed by dividing the weighted rainfall depth to the resulting streamflow. The long-term average value is computed to be C=0.14.

Table 4.2. Annual total rainfall and runoff coefficients in the Tikur Wuha sub-watershed

Year	Haisawita	Wendo Genet	Hawassa	Shashemene	Weighed rainfall* (mm)	Stream flow (mm)	C**
1981	1295	1314	1040	953	1110	106	0.10
1982	1403	821	992	1241	1132	108	0.10
1983	491	1158	1160	1108	947	136	0.14
1984	1348	1107	725	674	920	95	0.10
1985	1151	1229	902	892	991	87	0.09
1986	1079	1175	1194	565	1025	121	0.12
1987	1316	1241	955	1208	1123	110	0.10
1988	1035	931	957	887	954	126	0.13
1989	843	1191	1025	1073	987	126	0.13
1990	805	1277	751	962	847	146	0.17
1991	767	1124	889	594	809	131	0.16
1992	1287	1288	975	951	1078	129	0.12
1993	1133	1025	928	992	998	144	0.14
1994	1060	1250	861	745	921	132	0.14
1995	917	1403	1004	853	976	148	0.15
1996	1186	1305	1189	1207	1190	182	0.15
1997	1226	917	1055	1227	1114	143	0.13
1998	1265	943	1146	1175	1156	195	0.17
1999	817	1291	810	822	850	203	0.24
2000	1014	1161	822	986	931	135	0.14
2001	1298	1096	1022	662	1027	157	0.15
2002	1167	1031	920	338	878	173	0.20
2003	1037	1124	821	605	860	-	-
2004	1030	1314	896	669	919	185	0.20
2005	1304	821	998	689	999	162	0.16
							Average = 0.14

*computed as = value of (Haisawita x 0.285) + (Wendo Genet x 0.42) + (Hawassa x 0.195) + (Shashemene x 0.09)

**computed as the ratio of runoff from Tikur Wuha stream flow to the weighted rainfall for the sub-watershed

Figure 4.10 (below) and *appendix 5* depict the sequential regime shift of the runoff coefficient of Tikur Wuha. As depicted by the figure, the year 1997 (strong El Niño) is the breaking point. In the same way, the maximum runoff coefficient in 1999 (*table 4.2*) is likely attributed to the saturation of the soil as a result of high rainfall during 1997-98.

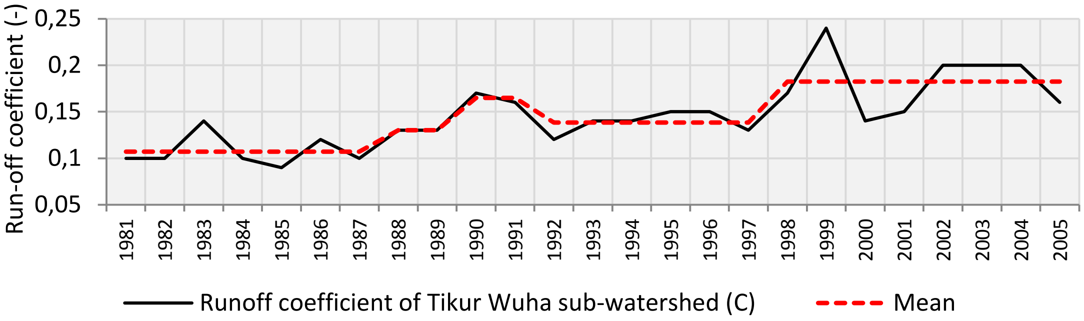


Figure 4.10. Shift detection in runoff coefficient of Tikur Wuha sub-watershed

4.5.6. Land use/cover changes: a potential anthropogenic factor

Often, the impact of climate change and human activities on hydrological variables cannot be distinguished (Uhlenbrook, 2009) or is still a challenge in hydrology (Elfert and Bormann, 2010). Climate and land use are key factors controlling the hydrological behavior of a watershed (Hörmann et al., 2005; Li et al., 2009). Technical details on the impact of land use on watershed hydrology is given in Maidment (1993) and other hydrology books. In terms of spatial scale, distinguishing the impact of land use changes on hydrology from the impact of climatic variability is more difficult at the watershed scale than at the plot scale or small watershed (Archer, 2003). Many studies have considered these factors separately. However, these factors do not act in isolation, but rather interact to affect ecosystem structure and function (Kulakowski et al., 2011). Their influence on the rainfall-runoff relationship is usually investigated through the analysis of long hydro-meteorological time series or by hydrological modeling (Tu et al., 2004).

Land use is a key factor controlling the hydrological behavior of watersheds and different approaches are thinkable to identify possible impacts of land use change on watershed hydrology. If long-term data series on the hydrological behavior as well as land use and other influencing factors are available, statistics can reveal the contribution of land use change to hydrological change in general (Elfert and Bormann, 2010).

A number of studies were conducted in Lake Hawassa watershed in relation to the impact of land use/cover of the local water cycle. Abrha (2007) attempted to assess its impact on ground water recharge. Gebreegziagher (2004) considered it as the most likely cause for the increasing tendency of runoff over time in combination with the effect of climate.

There could be different reasons for land use changes to occur and the social and physical forces that drive those changes are explained in the DPSIR analysis of *chapter eight*. *Table 4.3* presents some of the land use changes for the years: 1973, 1986, and 2000.

Table 4.3. Land use changes in Lake Hawassa watershed (units are in km^2) (Abrha, 2007).

	Agriculture	Grass land	Bush land	Shrubby wood land	Urban Area
1973	323.3	15.5	165.9	704.7	6
1986	466.2	59.5	180.3	548.6	8
2000	565.9	68.7	145.6	448.2	13

On average, 9.5 km^2 areas of shrub woodlands have been converted into other land uses types mostly into agricultural lands and instead, 9 km^2 new agricultural lands have been introduced. The general trends in land use/cover changes at country level also show similar tendency. For instance, forest cover in Ethiopia fell from 16% in the 1950s to 2.7% by the early 1990s, and continues to decline by nearly 1% per year as woodlands are converted to fuel wood, farmland and building materials (Shiferaw and Holden, 2001 *as cited in* Reynolds et al., 2010).

Generally, the long-term increasing trend of streamflow from Tikur Wuha sub-watershed (*figure 4.8*) without a corresponding increment in rainfall (*figure 4.6* and *4.7*) is found to justify the role of land use/cover changes at least in modifying the impact of climate. Chang (2007) also argued similarly where such situation indicates the modification of the hydro-system. This justification, which is based on statistical analysis of long hydro-meteorological time series, is supported by Tu et al. (2004) and Elfert and Bormann (2010).

4.5.7. Detection of regime shift in lake-evaporation (1986-2007)

The variation in the rate of evaporation from the surface of the lake is considered as one of the factors that affect the variations in water level. Monitoring of lake-evaporation has never been done for Lake Hawassa. Due to this situation, indirect methods were employed in our case. The first option was to use the pan-evaporation time series data and the second was to apply the Penman-Monteith model (Monteith, 1965; Penman, 1948) (*equation 4.15*). *Figure 4.11* shows the comparison between the estimates of lake-evaporation using both methods. A pan-coefficient of 0.75 was used as recommended by Ayenew and Gebreegziagher (2006), Legesse et al. (2003), and Ayenew (2002). The Penman-Monteith model uses five climate variables (minimum and maximum temperature, relative humidity, wind speed, and sun-shine hours) to compute the potential evapotranspiration (ETo) (*equation 4.13*), which is equivalent to evaporation from the surface of open water. In this study, the annual values of ETo were computed from monthly values of input parameters using CROPWAT 8.0 software.

$$ET_o = \frac{1}{L_v}\ \frac{\Delta(R_n - G) + \rho_a c_p(\delta_e)g_a}{\Delta + \gamma(1 + {g_a}/{g_s})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.13)$$

ET_o = Water volume evapotranspired (mm s^{-1})
L_v = Volumetric latent heat of vaporization. Energy required per water volume vaporized. (L_v = 2453 MJ m^{-3})
Δ = Rate of change of saturation specific humidity with air temperature. (Pa K^{-1})
R_n = Net irradiance (W m^{-2}), the external source of energy flux
G = Ground heat flux (W m^{-2})
c_p = Specific heat capacity of air (J kg^{-1} K^{-1})
ρ_a = dry air density (kg m^{-3})
δe = vapor pressure deficit, or specific humidity (Pa)
g_a = Conductivity of air, atmospheric conductance (m s^{-1})
g_s = Conductivity of stoma, surface conductance (m s^{-1})
γ = Psychrometric constant ($\gamma \approx 66$ Pa K^{-1})

The long-term annual average estimates of lake-evaporation are to the magnitude of 1432 mm (using the pan method) and 1406 mm (using the Penman-Monteith model) *(figure 4.11).*

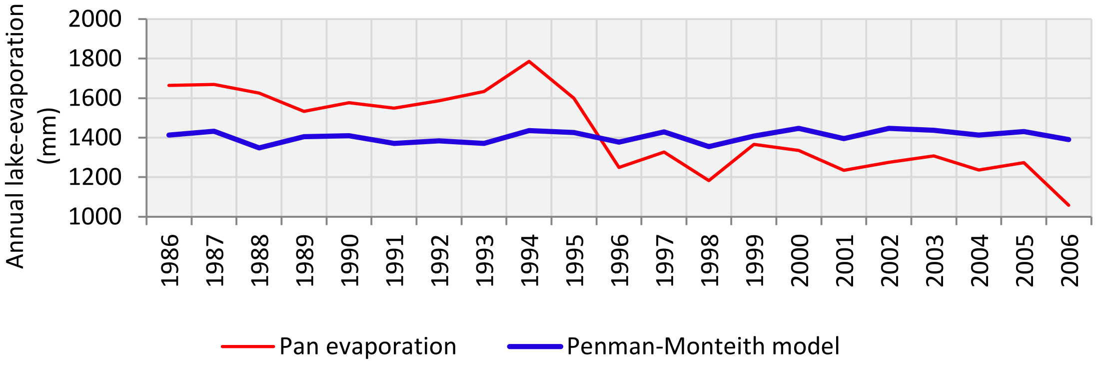


Figure 4.11. Comparison of lake-evaporation estimates of pan vs. Penman-Monteith model

As observed from *figure 4.11*, pan-evaporation appears to have a striking drop in annual magnitude between 1995 and 1996 and such drop is unusual and can be suspected of artificially induced resulting from changes in the position of instrument or recording technique. As witnessed by officials and experts of the meteorological agency (personal communication), there were no changes in data recording. Even though a general decline of pan-evaporation rate has been observed in many part of the world (Peterson et al., 1995; Chattopadhyay and Hulme, 1997), such drastic drop needs special attention. It is likely that some noise entered in the measurement of pan-evaporation after the year 1995 and needs to be further investigated.

In terms of variability across time, *figures 4.12* and *4.13* present the sequential regime shifts between the period 1986 and 2006.

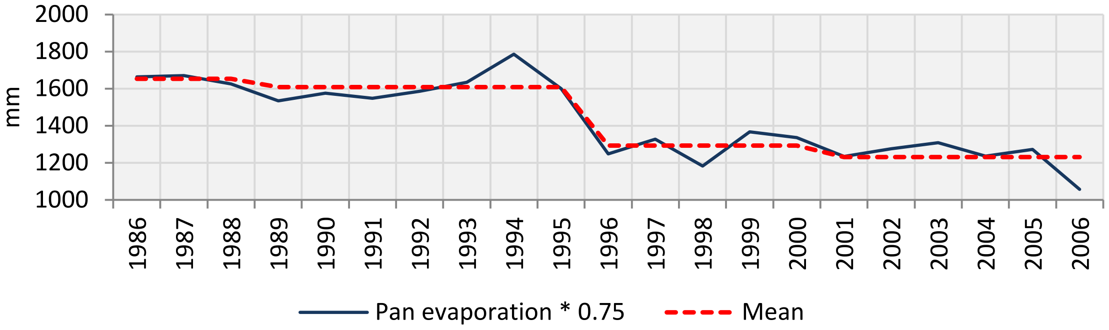


Figure 4.12. Regime shifts in lake-evaporation as computed from pan records (Data source: Meteorological Agency)

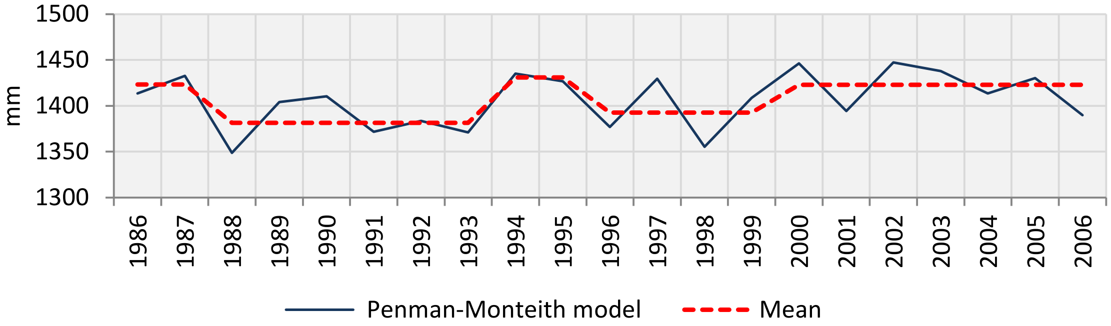


Figure 4.13. Regime shifts in lake-evaporation as computed by the Penman-Monteith model

As depicted by *figures 4.12* and *4.13*, the lake-evaporation exhibited significant regime shift at the year 1995 but this shift is pronounced in the estimates of pan-method. The effect of ENSO phenomena seems better shown by the Penman-Monteith method in which the year 1999 (strong La Niña) is found to be the change point.

4.6. Conclusions

The diverse statistical analyses of this chapter provide a plausible explanation for the interaction among the hydrology-climate-human components of the system. The hydrologic component includes lake level and streamflow; the climate component comprises evaporation, rainfall, and ENSO events; and the human component refers to the prevailing land use/cover changes.

More importantly, the evidences helped us to conclude about the effect of ENSO phenomena and climate shifts on the local climate and hydrology of the lake. Generally, it is observed that high lake level tends to follow moderate to strong El Niño and the reverse is true for La Niña events.

The general suggestions of this study supported the idea of Szestzay (1974) in which water level fluctuations of closed lakes are considered as meaningful indicators of climatic changes which strengthens the results of Nicholson et al. (2000), Arnell et al. (1996), and Bergonzini (1998) regarding the sensitivity of numerous lakes of East Africa.

The association of extreme lake level rises of Lake Hawassa to the occurrences of El Niño events (as in the case of 1998 flood) could have two management dimensions. On one hand, it would be difficult to mitigate the problem because of its dependence on macro-scale processes and on the other hand, those large El Niño events which are notorious for their extreme floods are acceptably predictable within period at lead times of up to two years (Chen et al., 2004). Climate forecasts are also shown to be more accurate during El Niño and La Niña events and furthermore, stronger ENSO events lead to greater predictability of the climate (Goddard and Dilley, 2005). These are opportunities to get alarms against the urgency of flood occurrences and it is recommended to mainstream the updated information regarding the probable occurrences of ENSO events and climate shifts in a regular emergency and preparedness actions to reduce the impact of potential flood risks.

Chapter 5. Simulation of the long-term water level variability of Lake Hawassa in the presence of regime shifts in water balance components

5.1. Introduction

In *chapter four*, it was shown that the lake level, rainfall, streamflow, and evaporation experienced sequential regime shifts during the study period. In this chapter, the effect of these regime shifts on the fitness of a lake level simulation model is hypothesized. As reported by Ayenew et al. (2007), Ayenew and Gebreegziabher (2006), and Gebreegziabher (2004), sharp rises in water level of Lake Hawassa had been occurred that could not be explained in terms of the water balance components. They explained the existence of divergence between the observed and simulated lake as it could be the effect of neotectonic activities, which in turn possibly affect the ground water flow regime. They also suggested the need for detailed investigation of hydro-climatic variables for better efficiency of the water balance model. Water balance technique is a means of solving important theoretical and practical hydrological problems (Chokolov and Chapma, 1974) and the idea of simulating the lake level variability in this study was conceived after recognizing the presence of hydro-climatic regime shifts that the simple spreadsheet water balance model may not account for. In addition, this study extends the previous water balance studies by about seven years.

5.2. Objectives of the chapter

The aim of this chapter is to simulate the long-term variability of Lake Hawassa water level using a simple spreadsheet water balance model and to examine how the model behaves throughout the study period.

5.3. Previous water balance studies of Lake Hawassa

Table 3.3 in *chapter three* presented the previous results of water balance modeling of Lake Hawassa. Among these, the work of WWDSE (2001) was one of the earliest available studies which computed water balance of Lake Hawassa for the period 1970-1998. This study used the historical records of over-lake rainfall, stream flow, surface runoff (using a runoff coefficient of 0.13 and 0.19) and evaporation (using pan coefficient of 0.8) together with the observed lake storage (as computed from change in lake level) to estimate the ground water flow component as the residual of the balance. The estimated magnitude of net ground out flow was 71 x10^6 m^3. The works of Ayenew et al. (2007) and Ayenew and Gebreegziabher (2006) followed similar approach. The assumed pan coefficient in these studies was 0.75 and a runoff coefficient for the un-gauged part of the watershed was 0.14. These studies estimated the constant annual ground water outflow of Lake Hawassa as 58 x10^6 m^3. Using the above values together with historical records of hydroclimatic series, it was shown that the observed and simulated lake level values were acceptably fitted for the period from 1981 to 1999.

5.4. Methods

5.4.1. Representing the water balance of Lake Hawassa

Water balance for a lake is based on the law of conservation of mass that states any change in water storage of a given lake during a specified period of time is equal to the difference between the amount of water added to the lake and the amount of water withdrawn from it and this balance can be constructed at any level of complexity (Lu et al., 2002). *Figure 5.1* represents the water balance of closed lakes (a kind of lake with no surface outflow).

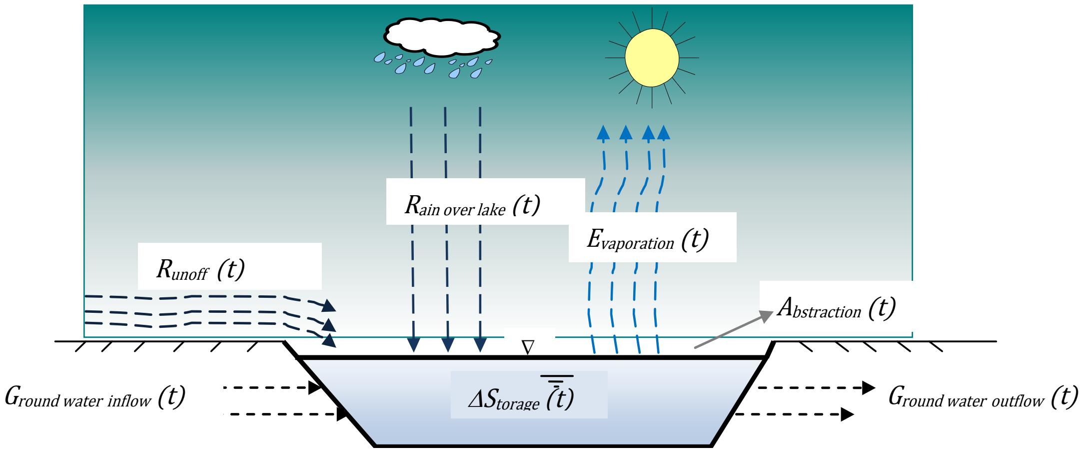


Figure 5.1. Schematic representation of the water balance components for a closed lake

The use of water balance model to investigate the hydrology of a lake is a common approach. For instance, Acreman et al. (1993) used this approach to explain the declining level of Lake Toba in Indonesia and Bechtand Harper (2002) to understand the anthropogenic impact upon the hydrology of Lake Naivasha in Kenya. Kebede et al. (2006) also employed similar approach to study the hydrological sensitivity of Lake Tana (Ethiopia) to variations in rainfall. The water balance of Lake Hawassa has been of wide interest for many years: initially because of scientific curiosity about the causes of the level rise, but lately for its influence on the infrastructure of the rapidly growing Hawassa town located in the eastern shore (Ayenew and Gebreegziabher, 2006).

According to the equation of continuity, the change in water level of a lake (ΔH) is controlled by the difference between the input and output of the water balance and the water surface area (A_L) (Szestzay, 1974) as shown in *equation 5.1* below.

$$\Delta H = \frac{\text{Total input} - \text{Total output}}{A_L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.1)$$

Whereby (A_L) may considerably vary with water level H and the aggregate flux terms of the numerator consist of a number of components largely differing from each other with regard to the dimension and time pattern of controlling physical processes.

The elevation-area-volume equations for Lake Hawassa were derived by Gebreegziabher (2004) as shown in *equations 5.2* and *5.3.* These equations were employed in this study.

$$\text{Lake Surface area } (m^2) = 4*10^6 d + 9*10^6 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.2)$$

$$\text{Lake volume } (m^3) = 2*10^6 d^2 + 1*10^7 d - 5.95*10^7 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.3)$$

Where d is the actual depth of the lake in meter

The extended mathematical relationship among the components of water balance in *figure 5.1* can be constructed based on conservation of mass as shown in *equation 5.4* below for hydrologically closed/terminal lakes like Hawassa in which the surface outflow component is omitted because of their terminal nature.

$$\Delta S_{torage}(t) = R_{ain\ over\ lake}(t) + Runoff(t) - E_{vaporation}(t) - A_{bstraction}(t) + G_{net\ ground\ water\ flow}(t) \ldots\ldots\ldots (5.4)$$

5.4.2. Quantification of water balance parameters

5.4.2.1. Over-lake precipitation

As shown in *figure 2.4*, time series rainfall records of Hawassa meteorological station represents the direct over-lake rainfall.

5.4.2.2. Stream flow into the lake

Tikur Wuha River is the only flow that has been gauged and time series of this data was used in this study.

5.4.2.3. Streamflow from the un-gauged part of the watershed

This component of the water balance was computed by adopting the runoff coefficient of the gauged sub-watershed as shown in *table 4.2*. The un-gauged portion of the watershed falls under the span of Hawassa and Yirbaduwancho meteorological stations with proportional share of 60 and 40% respectively (see *figure 2.4*). The two closed sub-watersheds: Muleti and Wendo Kosha with areas of 91.6 km^2 and 114 km^2 respectively (MoWR, 2010) were excluded from the computation. Refer *figure 2.9* for the locations of these two sub-watersheds.

5.4.2.4. Evaporation from the lake (E_{lake})

Evaporation from a water surface is rarely measured directly (Jones, 1992) and the use of standard pan with pan-coefficient is the most common method (Jensen 2010; Winter, 1981). Similar attempts were made by Ayenew and Gebreegziagher (2006), Legesse et al. (2003), and Ayenew (2002) in the Rift Valley of Ethiopia. This technique was adopted in this study with a pan-coefficient (k) of 0.75 following the recommendation of Ayenew and Gebreegziagher (2006), Legesse et al. (2003), and Ayenew (2002). As an alternative to the pan method, the Penman-Monteith model (Monteith, 1965; Penman, 1948) was used as described in *section 4.5.7* of *chapter four*.

5.4.2.5. Water abstraction from the lake (E_{lake})

As reported by Nidaw (1995) and Gebreegziagher (2004), there is no apparent evidence of water abstractions from the lake, but in terms of water that could have entered the lake, if not abstracted, are estimated to the magnitude of 22.56 x10^{5}m^3/year which totally accounts to about 1% of the total mean annual inflow. WWDSE (2001) and Ayenew et al. (2010) also confirmed the absence of abstraction. In this study, this component is assumed to be nil.

5.4.2.6. Consideration of ground water

The presence of considerable amount of net ground water outflow from the lake has been reported by WWDSE (2001), Ayenew et al. (2007) and Ayenew and Gebreegziagher (2006).

In terms of magnitude, WWDSE (2001) estimated the annual value to be 71 x10^6 m^3, and Ayenew et al. (2007) and Ayenew and Gebreegziagher (2006) estimated it as 58 x $10^6 m^3$. The average of the two estimates was used in this study.

5.4.3. Simulation procedure

The first step in simulating the lake level variability is the construction of the lake water balance. In this study, the long-term (1986-2006) water balance of Lake Hawassa is constructed on monthly basis according to *equation 5.4*. *Figure 5.2* represents the simulation procedure.

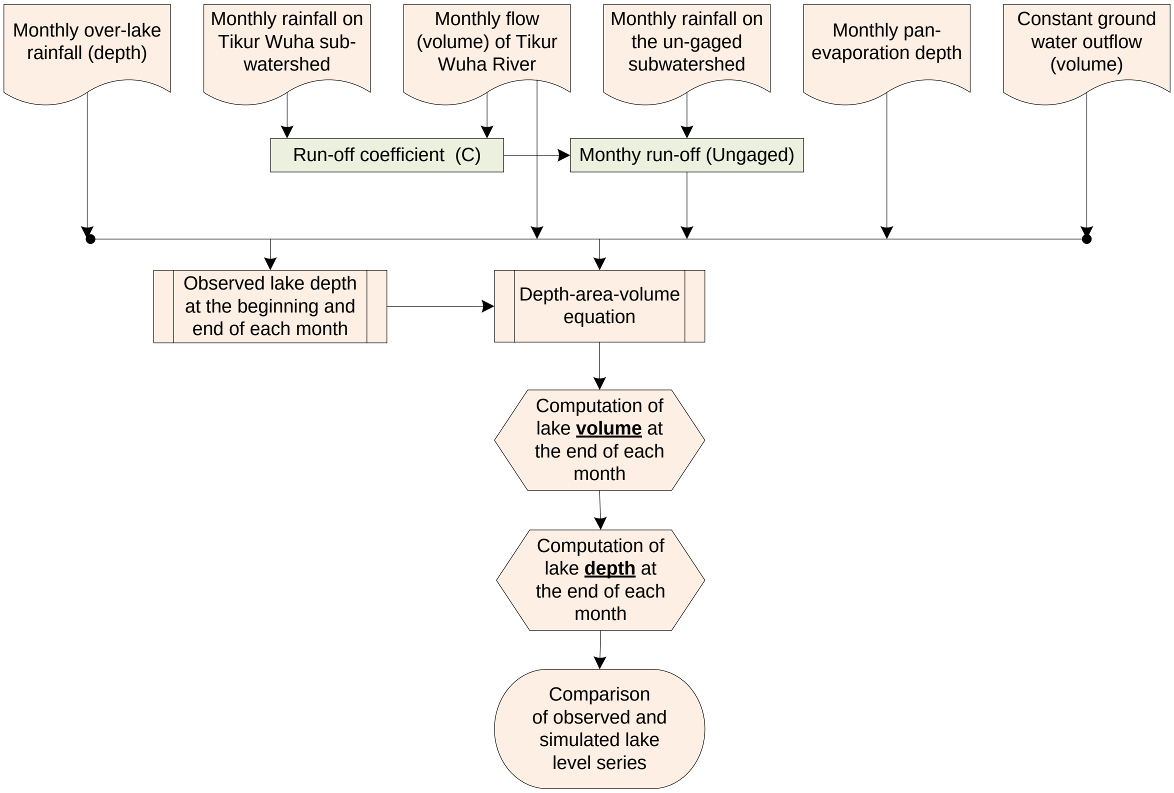


Figure 5.2. Flow chart of the lake level simulation procedure

As represented in *figure 5.2*, the raw data of the water balance equation were sequentially arranged on monthly basis in Microsoft Excel columns. Monthly rainfall and pan-evaporation data series are available in depth terms (mm) and stream flow records from Tikur Wuha River is available in volume term (m^3). Time series of streamflow from the un-gauged sub-watershed were generated by multiplying the runoff coefficients as computed for Tikur Wuha River (*table 4.2*).

The observed water depths at the beginning of each month serve as input for *equations 5.2* and *5.3* to calculate the corresponding lake surface area and stored volume. The volume of stored water at the end of a given month was calculated by adding the volume of on-lake rainfall, streamflow from the watershed and subtracting volume of evaporation and net ground water outflow from the amount of water computed at the beginning of the month. Once the volume of stored water at the end of each month was known, the corresponding lake depths were calculated by solving the positive roots of a quadratic equation as derived from *equation 5.3*. The simulation process started on January 1986 and the corresponding lake depth was 19.93m and its surface area of 88.72 km^2, with a storage volume of 934,209,800 m^3.

After the initial surface area and volume were set, the simulation process can continue in two ways. The first approach is the simulation "with updating" as *equation 5.7* and the second is "without updating" as *equation 5.8*, normally known as "simulation mode" in scientific literature. Model runs in updating mode normally can issue a reliable estimate at one time step ahead of the current time step, but the ultimate performance of a model depends on the model to give good estimates in the simulation mode. The simulation mode involves the use of previously estimated values as the input function in the model in order to issue a forecast (Kumambala and Ervine, 2010; Kachroo, 1992).

$$H_{Est}(t) = H_{Obs}(t-1) + \Delta H(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.7)$$

$$H_{Est}(t) = H_{Est}(t-1) + \Delta H(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.8)$$

Where $H_{Est}(t)$ estimated lake level and $H_{Obs}(t)$ is observed lake levelin a given period of time. In this research, the second approach (*equation 5.8*) was employed.

5.4.4. Updating procedure using Autoregression (AR)

Since the simulation of the lake level is going to run in "simulation-mode", it is sensible to expect the propagation of errors in the outputs of the model because of the reliance of a given output on the accuracy of other preceding outputs and such dependency is termed as autocorrelation. The autoregression (AR) model is one of the most favored updating procedures, which is extensively used in applied hydrology (Serban and Askew, 1991). This procedure is based on the modification or partial correction of the un-updated output variables of the model using their error estimates (Shamsedin and Connor, 1999).

According to Box and Jenkins (1976) and Kachroo (1992), an AR model of order p with mean of zero or an error time series can be defined as:

$$e_i = \sum_{k=1}^{p} \Phi_k e_{i-k} + a_i \qquad (5.9)$$

where e_i is the error at the i_{th} time period and Φ_k is the AR model parameter set and (ideally at least) a_i is a pure white noise sequence having mean zero and constant variance σ_a^2. Once the error series is determined, an AR model is separately calibrated on this series and subsequently used for forecasting the output errors. In principle, the success of this procedure depends on the degree of error persistence (Serban andAskew, 1991; Shamsedin and Connor, 1999).

5.4.5. Model efficiency test using Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) is a well-known normalized statistic that indicates how well the plot of observed versus simulated data fit the 1:1 line. It is computed as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2} \qquad (5.10)$$

where Y_i^{obs} is the i^{th} observed value in the series and Y_i^{sim} is the corresponding simulated value. Y_{mean} is mean of the observed, and n is the total number of observations. NSE values > 0.5 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates unacceptable performance.

5.5. Results and discussion

5.5.1. Results of water level simulation

As shown in *figure 5.5* the model was unable to capture the full range of lake level variability. The simulation up until 1996 was relatively acceptable but constant drift occurred afterwards. Similar divergence was reported by Belete (2009) while simulating the water level of Lake Abaya, another lake in Rift Valley Basin. Considering that the simulation before 1996 is acceptable, the error analysis was done for the remaining years after 1996 as presented in the upcoming section.

5.5.2. Result of residual error analysis

Figure 5.3 shows the procedure for error analysis. The persistent systematic error with continuous over-estimation (*figure 5.5*) is considered to be attributed to the accumulation of imbalances in the month-to-month error in model output. Such type of simulation is named as "simulation-mode" (without updating) in literatures and the model error is usually accumulated due to its auto-correlated elements (Kachroo, 1992; Kumambala and Ervine, 2010) and this may be particularly difficult to see unless analysis of the residual errors is done (Kumambala and Ervine, 2010). The errors between the simulated and the observed values can be compensated for through the use of implicit or explicit error updating procedures (Shamsedin and O´Connor, 1999). The predicted lake level at a given time step is a function of errors induced in the previously predicted values and its own. Such situation can be analyzed by studying the trend of the error propagation and fitting to error models like autoregressive (AR), so that persistent errors can be analyzed separately as shown in the following section. Similar approach was employed by Kumambala and Ervine (2010).

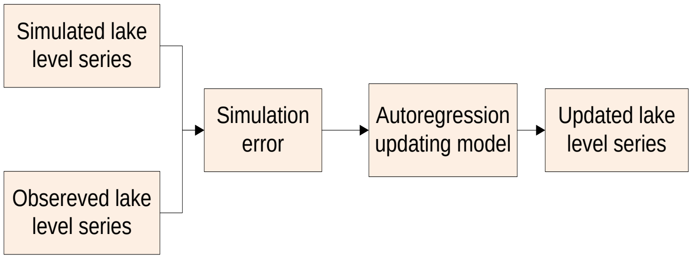


Figure 5.3. Schematic diagram of the linear Auto-Regressive (AR) updating model

Time series of model error was constructed by subtracting the observed lake level values from estimated values. From the result of residual analysis (*figure 5.4*), a linear relationship was observed between series of model error and time steps t (chronological sequence of months) with $r^2 = 0.97$ (*equation 5.11*).

$$\text{Error} = 0.042\ t \quad (r^2 = 0.97) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.11)$$

where t is the chronological sequence of months with t=1 for the first month (January 1996) and t=132 for the last month in the sequence (December 2006).The model errors (residuals) are assumed to be independent (uncorrelated) and normally distributed noise with mean equal to zero and constant variance (Ajami et al., 2006).

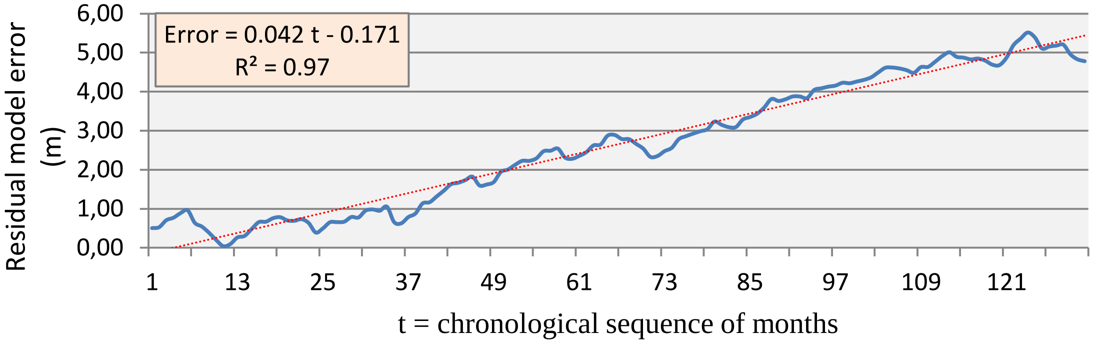


Figure 5.4. Trend of residual error (predicted - observed lake level values)
(Jan 1996-Dec 2006)

As shown in *figure 5.5*, the updating procedure improves the performance of the model with a Nash-Sutcliffe efficiency of 0.73.

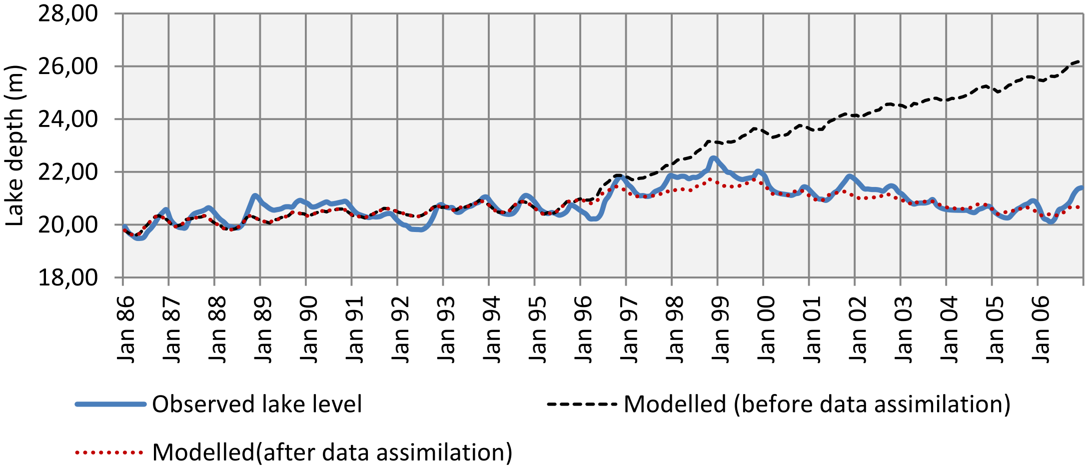


Figure 5.5. Simulated vs. observed lake level

5.5.3. Which components of the water balance show particularity at the year 1996?

The divergence of simulated and observed lake levels (*figure 5.5*) is assumed to result from the corresponding uncertainties in one or more input parameters of the model. *Figure 5.6* plots volumetric magnitudes of the five components of the water balance against time.

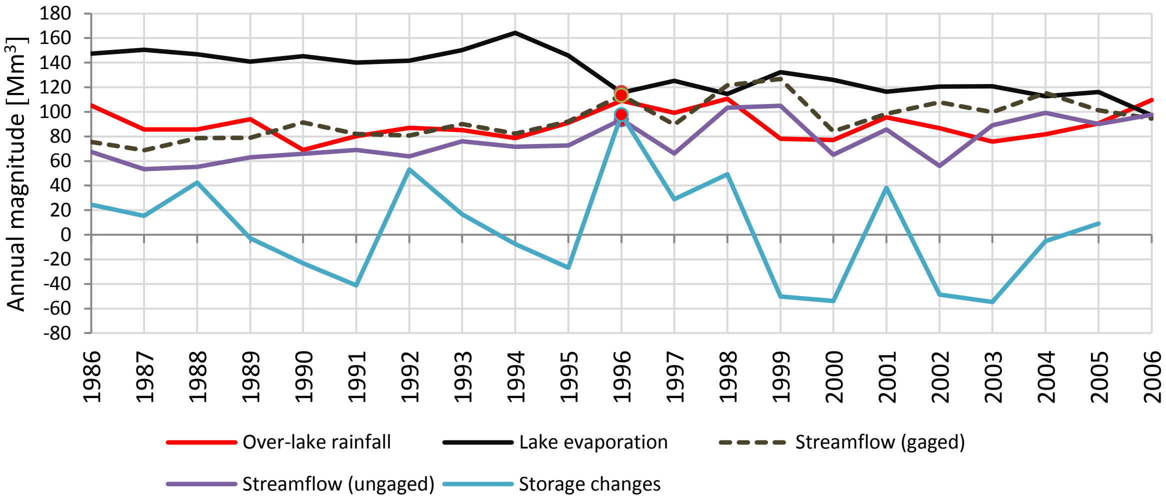


Figure 5.6. Annual magnitudes of water balance components

The visual interpretation of *figure 5.6* reveals that the year 1996 was so particular in that most of the water balance parameters experienced abrupt changes. The drastic drop in annual evaporation and the sharp rise in storage changes between 1995 and 1996 are the prominent particularities. The magnitude of annual rainfall also exhibited some increment during this period with a corresponding increment in runoff. Another variable that worth mentioning is the case of ground water flow in that the occurrence of particular imbalance on the ground water flow was reported by Yirgu et al. (1997), Ayenew and Gebreegziabher (2006), Gebreegziabher (2004), and WWDSE (2001). The analysis of ground water flow is not included in this study because of the absence of monitoring data.

5.5.4. Replacing the pan-evaporation by the Penman-Monteith model

As shown in *figure 4.11* (*chapter four*) and *figure 5.6*, evaporation shows a drastic drop in annual magnitude and such occurrence induces suspect on the records of pan-evaporation to be erroneous at some point. To account for such uncertainty, it was attempted to replace the monthly values of pan based lake-evaporation estimates by an alternative time series based on the Penman-Monteith model (Monteith, 1965; Penman, 1948) (which is based on minimum and maximum temperature, relative humidity, wind speed, and sunshine hours to calculate evaporation from open water surface) as described in *section 4.5.7* of the previous chapter. The result of the new simulation is presented in *figure 5.7* below.

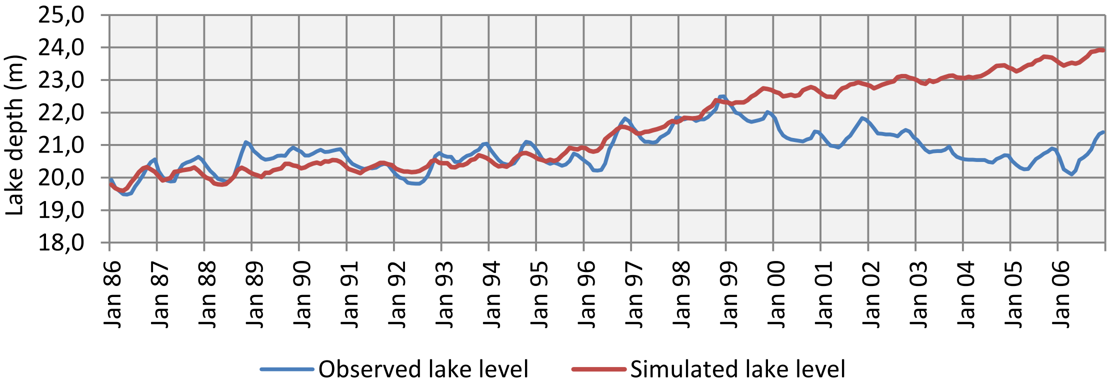


Figure 5.7. Simulation result after replacing pan-evaporation by Penman-Monteith model

As shown in *figure 5.7*, the simulation of the lake level is improved in the case of Penman-Monteith model. However, the divergence is still in existence except that it begins around the year of 1998. The situation partially shows the likely erroneous data of the pan-evaporation and such uncertainties shall be investigated in the future.

5.5.5. Annual magnitudes of water balance components

Annual magnitudes of the water balance components were computed as the sum of monthly values following *equation 5.4*. *Table 5.1* shows the time series of annual magnitudes of Lake Hawassa water balance components.

Table 5.1. Annual volume of some components of water balance of Lake Hawassa (Mm^3)

Year	Over-lake rainfall	Lake evaporation	Stream flow (gauged)	Stream flow (un-gauged)	Storage changes
1986	105	147	76	68	24
1987	86	150	69	53	15
1988	86	147	79	55	43
1989	94	141	79	63	-3
1990	69	145	91	66	-23
1991	80	140	82	69	-41
1992	87	142	81	64	53
1993	85	150	90	76	17
1994	79	164	82	72	-7
1995	91	146	92	73	-27
1996	109	116	113	94	98
1997	99	125	90	66	29
1998	111	115	122	103	49
1999	78	132	127	105	-50
2000	77	126	84	65	-54
2001	96	116	98	86	38
2002	87	121	108	56	-49
2003	76	121	100	89	-55
2004	82	113	115	99	-5
2005	91	116	101	90	9
2006	110	97	95	98	
Mean	**89**	**132**	**94**	**77**	**3**

N.B

- Negative values show the removal of water from the lake while the positive values show the addition of water.
- The gauged sub-watershed accounts for 625 km^2, whereas the un-gauged sub-watershed = 512.66 km^2. Area of the un-gauged sub-watershed was computed by subtracting the area of the lake (93.24 km^2), and the two closed sub-watersheds: Wendo Kosha = 114 km^2; and Muleti = 91.6 km^2 from the total watershed area = 1436.5 km^2

5.6. Conclusions

This chapter is not the first attempt to simulate the lake level variability of Lake Hawassa; rather it is a sort of updating the existing water balance estimations. It also shows the potential future inconveniences that would occur due to uncertainties in some of water balance components.

Regarding the estimated magnitudes of long-term annual water balance components, the over-lake precipitation (89 Mm^3), evaporation (132 Mm^3), and gauged stream flow from the gauged sub-watershed (94 Mm^3) are about the same magnitudes as compared to the previous results (*table 3.3* of *chapter three*). Streamflow from un-gauged sub-watershed (77 Mm^3) is higher than the estimates of Shewangizaw (2010); and lower than the estimate of WRDB (2007) and WWDSE (2001). Such disagreement seems to be associated with the consideration of the two closed sub-watersheds: Wendo Kosha and Muleti. Gebremichael (2007) computed magnitude of the combined (gauged and un-gauged) streamflow which is a little lower than our estimate. The magnitude of storage changes (3 Mm^3) could not be compared to the previous results because of the absence of comparable estimates.

Chapter 6. The effect of recent sedimentation on the storage capacity of Lake Hawassa

6.1. Introduction

Most of the lowlands in the Central Rift Valley of Ethiopia are arid or semiarid and in degradation, with frequent occurrence of droughts. Soil erosion by water during the rainy season is a serious problem in the region, leading to declining agricultural production, decreased food security, and a sedimentation risk for water bodies (Meshesha et al., 2012). This situation has been accelerated by many human activities such as clearing forests and woodlands, complete removal of crop residues, and overgrazing, exacerbated by poor soil management and land use practices (Bekele, 2003).

Soil erosion causes accumulation of sediment in lakes and reservoirs, which results in the degradation and impairment of use of these water bodies (Fitzpatrick et al., 1987). Sedimentation has undesirable impacts on water quality, storage capacity, recreational value, and natural lake bed habitat of natural and/or artificial lakes. For instance, John Redmond Reservoir in US lost 37% of its storage capacity in 50 years (Martinko et al., 2011). LIA (2010) also affirmed the impact of sedimentation in causing reductions in water depths, smothering animals living in the bed, reducing light penetration (water clarity), and hence the water depth in which aquatic plants with roots in the bed can grow. Drying-up of some lakes in Ethiopia, such as, Lake Haromaya in the Eastern part (Alemayehu et al., 2007) and Lake Cheleleka in the upstream of Lake Hawassa (see *figures 6.5, 6.6* and *6.7*) are among the live examples for the impact of sedimentation on the reduction of storage capacities and then disappearance of the entire lakes.

Recent siltation of Lake Hawassa has been perceived as one of the environmental dangers threatening the lake that can lead to changes in its morphology, which may decrease the water storage capacity that in turn contribute to the rise of the water level. There have been many speculations on the impact of sedimentation process on the storage capacity and lake level rise such as Esayas (2010), Gebreegziabher (2004), and Geremew (2000).

The study of sedimentation records has been widely used in palaeolimnological reconstructions to evidence long-term trends of the climate change during the geological years (Tiercelin et al., 1988) and these techniques often used only little number of cores (point data) from the deepest part of a lake (Terasmaa, 2011). Such kind of study was conducted for Lake

Hawassa by Lamb et al. (2002). According to them, sediment accumulation rate in the lake was estimated to vary between 1.2 and 2.0 mm/yr (mean rate 1.7 mm/yr) but this magnitude is valid in time scale of centuries and less informative in explaining the contemporary situation. So, it is timely task to study the recent in-lake sedimentation.

The most conventional technique and accurate determination of sediment load being carried to a lake by streams is to measure the flow rate and sediment concentration of the inflowing waters just upstream of the lake. The other conventional methods involve periodic bathymetric surveys of the lake (limgis, 2001). Temporal comparison of bathymetry maps is an indicator for environmental changes like lake or reservoir sedimentation. From this information, lake ecosystem functioning, life time of reservoirs or erosion-sedimentation rates of watersheds can be derived (Dost and Mannaerts, 2006).

The use of maps to study sediment accumulation in reservoirs is a common practice in many parts of the world. For instance, prior to the mid-80’s, the Natural Resource Conservation Service (NRCS), formerly known as the U.S. Soil Conservation Service (US SCS), hydrographically surveyed Triadelphia and Rocky Gorge Reservoirs approximately once every 10 years to determine the amount and rate of sediment accumulation. The approach in this case is to calculate the temporal differences of reservoir capacities between long-term consecutive mapping periods. For this, the range method, which utilized a number of transects to determine the cross-sectional area of the reservoir at different locations and reservoir volumes are calculated and from that, the deposited sediment volumes are deduced (Ortt et al., 2008). Repeated bathymetric surveys can provide significant insight into the nature of sedimentation within a reservoir. Changes in reservoir bottom topography can be monitored over time to provide an overall estimate of the sediment accumulation rate and spatially explicit representation of sediment accumulation (DeNoyelles and Jakubauskas, 2008).

Despite the importance, the in-lake sedimentation of Lake Hawassa has never been monitored because of some perceived reasons such as cost, little awareness about the degree of the problem, and probably due to the absence of an explicitly responsible organization for such activities.

In response to the above situations, the assessment of in-lake sedimentation helps to recognize its effect on the storage capacity of Lake Hawassa. At this moment, the bathymetric approach appears to be an attractive and judicious choice because of the presence of previous bathymetry maps to compare with the new one.

6.2. Hypothesis and objectives of the chapter

In accordance with the hypothesis on the effect of recent sedimentation on the storage capacity of Lake Hawassa, the objectives of this chapter are:

- To produce a new bathymetry map (of 2010) from a new hydrographic survey and to compare it with the old map (of 1999);
- To demonstrate the application of comparative analysis of the two bathymetric maps in estimating the amount of sediment accumulation; and
- To compare the sediment volume with the storage capacity of the lake.

6.3. Materials and methods

6.3.1. The old bathymetric map (1999)

The first intensive bathymetry survey was done by Water Works Design and Supervision Enterprise in 1999 using Bathy 1500 echo sounder (Version P02585). Echosounder is a device for measuring depth of water by sending pressure waves down from the surface and recording the time until the echo returns from the bottom (the free dictionary*: accessed in 2012*). The technical specifications are shown in *table 6.1*. The output of this survey was obtained from the archive of respective office in the form of hard copies as four A1 sized original blue prints with a scale of 1:10000. To keep the originality of the information, these A1 sized papers were scanned with a 300 dpi resolution scanner in University of Bonn (Germany) at the Department of Geography and the scanned images were georeferenced (*figure 6.2: a*) to fit the lake using the standard georeferencing technique available in ArcGIS10.

6.3.2. Tying local bench marks with standard elevations

Since the start of monitoring the lake level by Ministry of Water Resources, the data has been recorded relative to the local bench marks. The elevation of the datum for water level monitoring station of Lake Hawassa which is coded as 082004 and operated by MoWR was set to be 1678.17 m.a.s.l. (WWDSE, 2001). The new survey also relied on this setup for the sake of future comparison.

6.3.3. The new bathymetric survey (2010)

Before the commencement of the bathymetry survey, the SPOT5 satellite image of the lake was gridded with 500 x 500m spacing and 337 points (*figure 6.2: c*) were generated to cover the entire surface area of the lake. The contour lines of the old bathymetry map were interpolated and converted into raster surface using ArcGIS 10 software and then with the use of "extract values to points" option, the old elevation of each gridded locations were extracted from the old bathymetry map as a kind of re-sampling.

The echosounder generates acoustic pulses for bottom recognition (water/sediment interface). The data were collected as discrete x, y, z points where x and y are geographic coordinates of the discrete points and z represents the depth of the lake bottom as measured from the surface of the lake. A sonarmite echosounder, with technical specifications as shown in *table 6.1*, was used, and a stadia rod was used to measure water depth shallower than 0.3m where large grasses dominate. The basic components are: a recorder, the transmitting and receiving transducer and a power supply. A total of 32 to-and-fro trips were made to cover the entire lake surface during the survey which was made between December 2010 and January 2011.

Table 6.1. Main technical parameters of the two echosounders

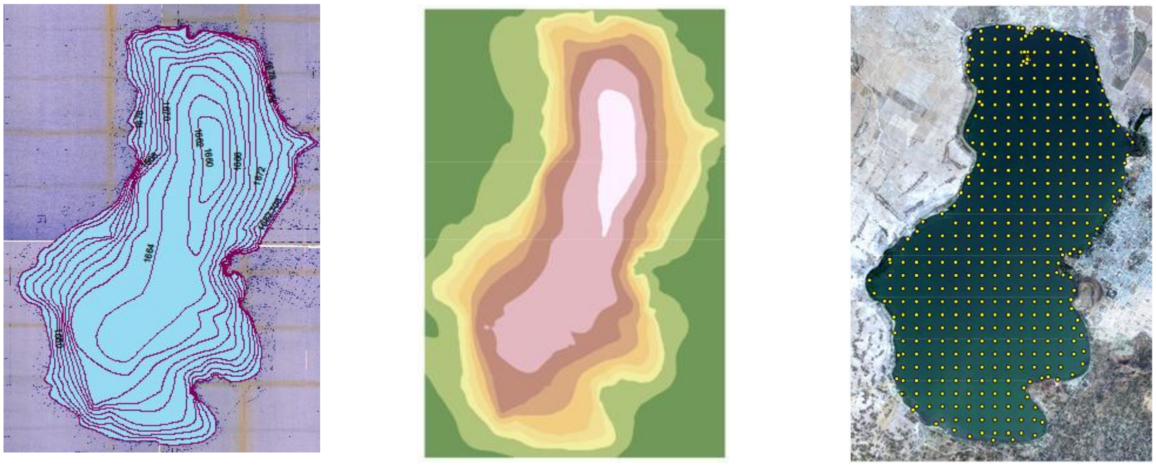
	Old (1999)	**New (2011)**
Brand name	Bathy 1500 echosounder (P02585)	Sonarmite echosounder
Transducer frequency	33/200 kHz (Dual)	235 kHz
Minimum depth	0.5 m (transducer dependent)	0.3 m
Maximum depth	1000 m	75 m (software limit)
Beam pattern	8 to 24 Degrees	8 to 10 degrees
Accuracy	+ / - 0.025 m (*for 0-40m depth*)	+ / - 0.025 m

(a) Bathy 1500 echosounder (b) Sonarmite echosounder

Figure 6.1. Partial view of echosounders for the old and new bathymetry surveys

6.3.4. Assessment of sediment by topographic differencing technique

The bathymetric approach in this study was based on a direct comparison of lake bottom elevation at two different time periods (topographic differencing technique), first in January 1999 (referred as old map) and second in December 2010 and January 2011 (referred as new map) to detect the changes. The approach was based on the procedure used by Ortt et al. (2008) that consisted of an assessment phase and of a historical comparison phase. The distribution of sediment accumulation thicknesses and volume in the lake was determined by comparing the new and old bathymetry maps. The sediment thickness map was generated by subtracting the new bottom elevation from the old values.



(a) Original blueprint (1999) (b) Interpolated raster (1999) (c) New measurement points (2010)

Figure 6.2. Basic steps in the topographic differencing between the two bathymetry maps

6.4. Results and discussion

6.4.1. Estimation of sediment thickness and distribution

The result of topographic differencing between the two bathymetry maps is presented in *figure 6.3*. It is found that the average sediment thickness between 1999 and 2010 was to the magnitude of 14 ± 5cm. The ± 5cm allowance is given to the estimation due to the accuracy level of the echosounders (refer *table 6.1*). If a constant annual rate is assumed in the period, the sedimentation rate would be 1.2 cm/year. Computation of sediment volume is discussed in the next section. At the moment, we cannot compare this value with other results due to the absence of recent sediment studies in the region. In terms of geological scale, which is less informative regarding the recent situation, Lamb et al. (2002) estimated the average sedimentation rate in Lake Hawassa to the magnitude of 0.17 cm/year placing the basal date at 6400 ^{14}Cyr. Generally, as compared to the recently expanding gullies and the presence of continuous land use changes as reported by Abraha (2007); Shewangizaw and Michael (2010); Dessie and Christiansson (2008); WWDSE (2001); and Wagesho et al. (2012), the magnitude of sedimentation rate seems to be underestimated or below the expectation of many stakeholders. The distribution of sediment thicknesses over the entire lake bed is shown in *figure 6.3* below.

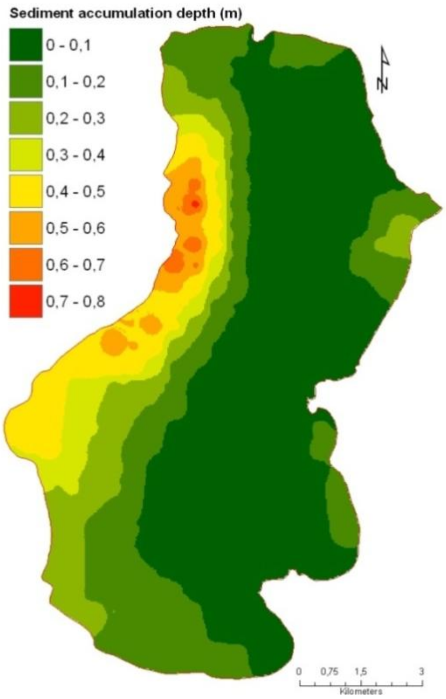


Figure 6.3. Spatial distribution of sediment thicknesses during the period 1999-2010

According to *figure 6.3*, sediment accumulation thicknesses range from <3 cm to 73cm. It is higher at the western end of the lake and becomes lower while approaching the eastern end where the city of Hawassa is located. The maximum deposition occurred at the western part of the lake. Some of the northern parts and the entry of Tikur Wuha River also show comparatively higher sediment accumulation than the rest of the areas. The linkages of such sedimentation patterns to the catchment characteristics are discussed in *section 6.6*. Generally, sedimentation rate is consistent with the degradation and pumice nature of the western sub-watershed.

6.4.2. Sediment volume and its impact on the storage capacity

In terms of volume, the total accumulated sediment between 1999 and 2010 is estimated to be in the magnitude of 0.0133 km^3or 13.3x$10^6 m^3$ (taking the surface area of 94.85 km^2 as computed by ArcGIS based on depth measurement points) which is about 1.2% of the total volume in twelve years. Assuming a constant rate over the period, the annual sedimentation rate becomes 0.0011 km^3 or 1.1x10^6 m^3. As per this rate, the annual reduction in storage capacity due to siltation is about 0.08%, which is a little higher than High Aswan Dam in Egypt (0.05% between 1967 and 1991); and lower than Imagi reservoir in Kenya (0.8%); Sennar (Makwar reservoir) in Sudan (0.6% between 1925 and 1986); and estimated global average rate for annual loss of reservoir capacity of 1% (Douglas et al., 2001). The specific sediment yield, which is the total annual sediment volume divided by the sediment contributing area of the catchment, is estimated to be 967 m^3/km^2/year. One could imagine that the effect of sedimentation is minimal in Lake Hawassa by looking at its physical magnitude, but the reality is that this sediment carries chemicals from the watershed which potentially affect the function of the watershed. So, this result should not be considered as discounting the devastating effect of the sedimentation process on the ecosystem.

6.5. Methodological limitations/ shortcoming /challenges and solutions

The practical implication of our results is a more optimistic view towards the possibility of estimating sediment depth and volume based on two bathymetric surveys. The success of such estimation will be more strengthened after consecutive similar survey. Meanwhile, the methodological problems encountered and their solutions while undertaking this study were presented in the following paragraphs.

One of the methodological problems in this study was the difference in the formats of the two maps which did not integrate directly. The old map was line data whereas the new map was point data. To bring the two maps into a common format, the old line data was converted into continuous surface in raster format using Kriging technique of ArcGIS 10. The Kriging procedure generated an estimated surface from the scattered set of contour lines with z-values. Hence, the "extract values to points" option of the spatial analyst tool was used to extract the values of old bed elevation for each x,y coordinates of the new survey. By doing so, the x,y,z values of the old bottom elevations were determined before the new survey and these values were fed to the GPS to navigate into the point of interest. This technique is also assumed to be more convenient for future comparison of changes in lake morphology.

The presence of large number of outliers (31 out of 337 pairs of values = 9 %) was another problem in this approach. These outliers showed unrealistic elevation differences in that the former elevation is greater than the new ones, which is unlikely and replaced by average values of the eight points in the neighboring grids. The likely sources of the outliers might be the interpolation technique and/or the accuracy of depth measurements. More accurate result would come up if the two maps were generated by the same instrumentation and intensity.

In addition, most of the surveys were conducted between 11:00 a.m. - 4:00 p.m. because there happened less wave occurrences during these hours. But, in few cases, there have been waves with a potential to change the depth measurements and possibility to tilt the transducer away from its vertical position. As a solution, repeated measurements were taken together with the consideration of the wave heights. To avoid the potential effect of depth measurements at the border of the lake where in-lake vegetation grow, a manually operated stadia rod was used to directly measure the water depths.

6.6. The linkage of in-lake sedimentation to the sources in the watershed

The sedimentation process is dependent on a multitude of biophysical and anthropogenic factors, such as the size of the lake, the size of watershed, soil type, climate, land cover, and land use (Dost and Mannaerts, 2006). Such linkage is considered in *chapter seven* which integrates nine factors affecting sediment production and transport processes. Those characteristics of the watershed which are not included in *chapter seven* are discussed in the upcoming sections.

6.6.1. Linkage to gully density in the watershed

Gully erosion is the dominant type of erosion in the watershed and it is considered as a significant process for delivering sediment to the lake. Due to this, it was attempted to compare the extent and pattern of gully erosion across the watershed with the pattern of sediment accumulation in the lake. To this end, the spatial distribution of gully density is assessed based on the data provided by MoWR (2010). Accordingly, the watershed contains 750 segments of gullies with a total linear length of about 668 km which are concentrated on the Western side of the lake (*figure 6.4*). As shown in the figure, the western part of the watershed is highly dissected by gully networks and it is in accordance with the result of in-lake sedimentation *figure 6.3*.

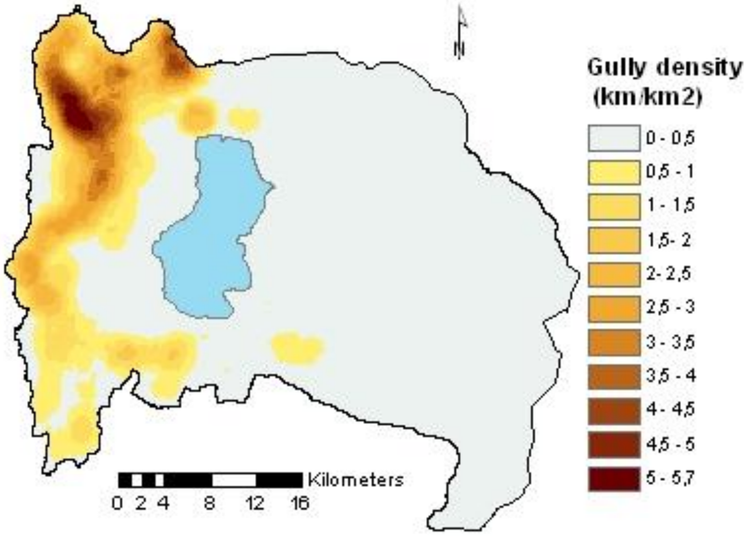


Figure 6.4. Map of gully density and pictures of active gullies in the watershed [Sources of the raw data: MoWR (2010)]

6.6.2. Linkage to the disappearance of Lake Cheleleka

In the nineteenth century, Lake Hawassa and Cheleleka had been a single lake (Grove et al., 1975) and Lake Cheleleka was serving as a natural regulator of flow, sedimentation, and biogeochemistry for Lake Hawassa. The progressive silting up of Lake Cheleleka over the last 35 years (*figures 6.5; 6.6* and *6.7*) is an example to the degree of sedimentation problem in the watershed.

Unfortunately, the rate of siltation could not be estimated due to the absence of data but the rate of shrinkage in lake surface area was monitored by a series of images. Topographic map with a scale of 1:50,000 was used to delineate the surface area of Lake Cheleleka in the year of 1972; satellite imageries of thematic mapper (TM) was used for 1986 and 1995; ETM for 2000 and Spot5 for 2007.

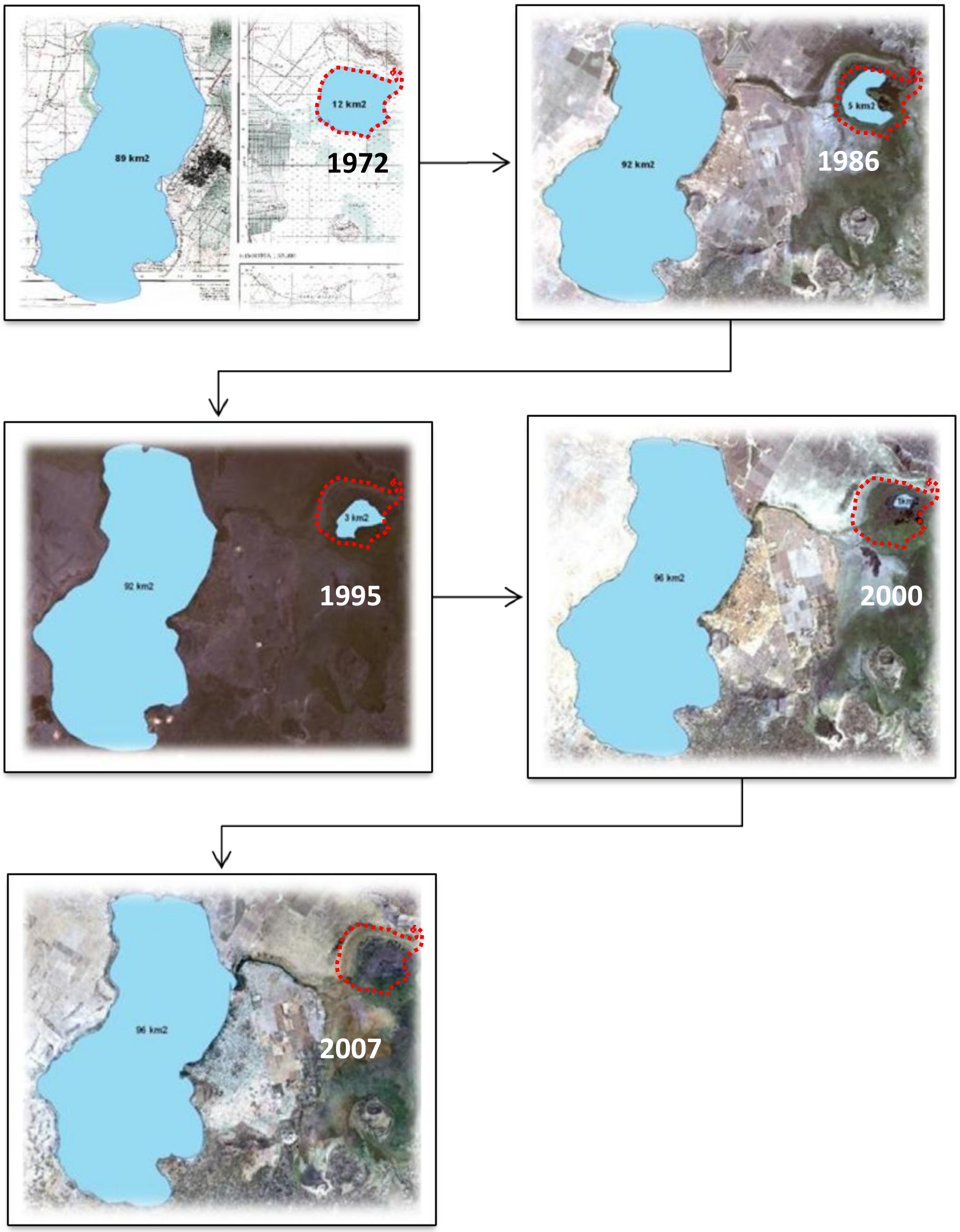


Figure 6.5. The disappearance of Lake Cheleleka in the watershed [Source: Own study]

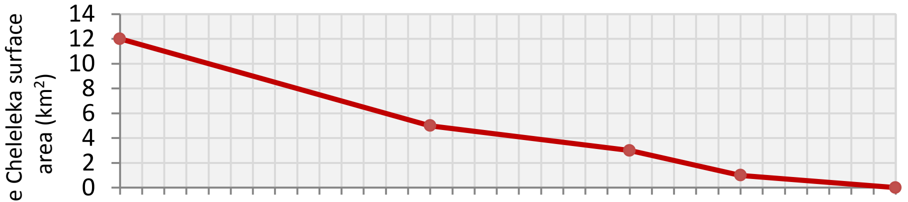


Figure 6.6. Time series of changes in the surface area of Lake Cheleleka

Figure 6.7. Current view of the former Lake Cheleleka (2011)

In 1972, the surface area of Lake Cheleleka was 12 km^2. In 1986, it shrank to 5 km^2. The 1995 image shows that the surface was reduced to 3 km^2, and the 2000 image evidenced the shrinkage of the surface area down to1 km^2. The disappearance of Lake Cheleleka is shown in the 2007 image. Currently, the area is serving as a grazing land as shown in *figure 6.7*. Similar silting up of a large lake, Lake Haromaya in the Eastern part of Ethiopia, was reported by Alemayehu et al. (2007) as shown in *figure 6.8* below.

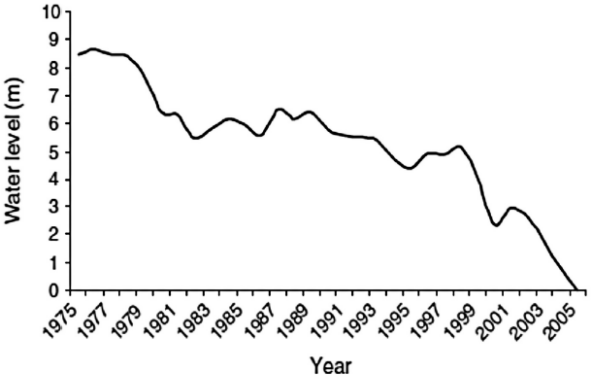


Figure 6.8. Dropping down of Lake Haromaya till drying up [Source: Alemayehu et al., 2007]

Generally, the susceptibility of Lake Hawassa for siltation seems high as observed from the diminishing rate of Lake Cheleleka. Lake Cheleleka was serving as a natural silt trap, but currently its damming effect is reduced exposing Lake Hawassa to an increased siltation.

6.7. Conclusions

This study is a first attempt to quantify the amount of contemporary sediment, to our knowledge, in Lake Hawassa and found to provide important information about the effect of sediment on the storage capacity of the lake. The case of sedimentation in a lake is different from the water balance components in affecting the lake level changes. That is because once this sediment joins the lake, it settles and remains there by creating permanent change in the capacity of the lake. In terms of storage capacity, the annual reduction due to siltation is found to be low (0.08% of the total volume) suggesting that the silting-up of Lake Hawassa is less than global average rate of reservoirs' sedimentation.

Regarding the bathymetric approach employed in this study, the technique is found to give an insight to the depth and volume of in-lake sedimentation and provides important baseline information. The results suggested that the approach is promising and provide acceptable evidence against the hypothesis despite its limitations. Furthermore, the requirement of small commitment of time and no involvement of permanent monitoring make the approach more applicable.

Chapter 7. The linkage of sedimentation in Lake Hawassa to the watershed characteristics: an application of PSIAC model

7.1. Introduction

Erosion/sediment risk maps are specialized form of land resource evaluations, as they classify basins of similar erosion/sediment risk degree (Gournellos et al., 2004). Erosion risk assessment methods can be used for various tasks such as: assessment of average pattern of erosion risk, identification of high risk areas, identification of hot spots, location of depositional and major concentrated flow areas, detailed erosion and deposition pattern and effects of conservation measures, and detailed impact of erosion on roads (Blinkov and Kostadinov, 2010). Land use and soil conservation planning also require erosion risk maps and this mapping can be done using deterministic erosion models that describe processes and quantitative outcomes. However, the common drawback of these models is that they are developed for different regions than where they are applied (Vrieling et al., 2002). Vrieling et al. (2002) noted that a qualitative approach can be more effective in erosion risk mapping than the use of models that were not developed for the region to which they are applied. Morgan (2005) also considered the attempts of using a model for conditions outside those specified as bad practice and, at best, speculative.

Generally, three types of approaches exist to assess erosion risks: qualitative approach, quantitative approach, and model approach. All these methods vary in their characteristics and applicability (Eckelmann et al., 2006). The ideal erosion model considers all of the factors controlling soil erosion as it constitutes: the erosivity of the eroding agent, the erodibility of the soil, the slope of the land, and the nature of the plant cover (Morgan, 2005); but in practice such consideration is not yet achieved. Depending on the scale, a single or combination of indices has been used by different researchers to assess the erosion risks. For instance, Stocking and Elwell (1976) used mean annual erosivity values to assess the generalized erosion risk in Zimbabwe. Similar attempts were made by Wischmeier and Smith (1978) for USA; Hudson (1981) for Bulawayo and Harare; and Rowntree (1983) for Kenya. Stocking and Elwell (1973) devised a factorial scoring system for rating erosion risk in Zimbabwe to the scale from 1 (low risk) to 5 (high risk) in respect of erosivity, erodibility, slope, ground cover, and human occupation. Vrieling et al. (2006) also showed the use of information on the steepness of slopes and vegetation cover to map erosion risk in a watershed. According to

Grimm et al. (2002), a problem with most methods based on scoring is that the results are affected by the way the scores are defined.

In the same way, assessment of spatial variations of sediment yield potential provides information for prioritizing watershed management interventions. Watershed sediment yield is the product of all sediment producing processes and sediment transport within a watershed (Vente, 2009). The important factors affecting sediment yields are: size of drainage area, topography, soils, cover conditions, and degree of channelization (Robinson, 1977). Traditionally, the problems in predicting sediment yield at the basin scale are related to model's high data requirements (Vente et al., 2005) and these data are predefined to fit to the specific model. The pre-defined nature of those models does not allow the use of other data which are even better or latest. Such nature of the existing numerical models hinders their application in many regions. On the other hand, there exists local and global data base like DEM, satellite images and some kind of major land use/cover classifications and the less strict model that can accommodate available environmental information for its input can easily be adopted in many areas as far as it can be validated to the region. The more appropriate technique at this moment is assumed to adopt less strict model and modify its parameterization and validate in an area.

Though they have received only limited attention in the international literature, there are some models that purport to have holistic approach, at least to some extent. Often, these models are a combination of descriptive and quantitative procedures to characterize a drainage basin and result in a quantitative or sometimes qualitative estimate of sediment yield in a basin. Therefore, these models can be classified in general as semi-quantitative (Vente et al., 2005).

The PSIAC (Pacific-Southwest Inter-Agency Committee) model is one of the semi-quantitative models (PSIAC, 1968) and it was employed in this study. The idea of employing a semi-quantitative model in Lake Hawassa watershed was conceived in response to the absence of validated model to readily apply and compare the output for the estimation of lake sedimentation.

7.2. Research questions and objective of the chapter

Triggered by the sedimentation rate of the lake (that was estimated in *chapter 6*), other research questions were raised as: "Where is the source of sediment?" and "How is it linked to the watershed characteristics?".

In addressing the above questions, this chapter targets:

- To characterize the watershed in terms the nine sediment yield factors (geology, soils, climate, topography, land use, ground cover, run off, upland erosion, and sediment transport in the stream channel);
- To compare the output of PSIAC model with previous findings.

7.3. PSIAC model

Table 7.1 presents different techniques of sediment source estimation and the various erosion/sediment processes to be estimated by the techniques. Further description can be referred from Gee and MacArthur (1996).

Table 7.1. Sediment source estimation techniques

Method/model	Sheet and rill erosion	Gully erosion	Channel bed and bank erosion	Mass movement	Average annual yield	Single event yield
USLE	▨				√	
MUSLE	▨					√
RUSLE	▨				√	
PSIAC	▨	▨	▨	▨	√	
Aerial photography	▨	▨	▨	▨	√	√
Topographic survey		▨	▨		√	√
Thompson or SCS TR32		▨			√	
Dendy and Bolton	▨	▨	▨	▨	√	
Strand and Pemberten, USBR	▨	▨	▨	▨	√	
SCS yield rate map	▨	▨	▨	▨	√	

(Source: Gee and MacArthur, 1996)

According to PSIAC (1968), the model is probably the most known semi-quantitative model which was developed by the Pacific Southwest Inter-Agency Committee (PSIAC) for application in arid and semi-arid areas in the southwestern USA. The model was recommended for use in broad planning purposes and for basins of at least 25 km^2. The PSIAC model consists of a rating technique that characterizes a drainage basin in terms of sensitivity to erosion, possibilities for sediment transport and flood plain storage, the protective role of vegetation, and the influence of human land use practices.

Nine factors characterize a watershed in PSIAC model with a score to each factor (*table 7.2* and *7.3*). The first division includes watershed parameters related to geographic features, namely: X1= geology; X2= soils; X5= topography; X7= land use; and X6= ground cover. The aforementioned parameters are natural parameters related to the geographical features. These parameters respond to other parameters, such as X3= climate (rainfall), which causes erosion and the development of gullies and rivers. The response of the geographic parameters to the rainfall is represented by the following parameters: X4= run off; X8= upland erosion; and X9= sediment transport in the stream channel. In PSIAC, the most important parameters are X8 and X9 (Seyed et al., 2008) which together can form one third to one-half of the total parameters together.

Table 7.2. PSIAC parameters and their diagnostic criteria [modified after PSIAC (1968)]

	PSIAC parameters	**Description**	**Included in this factor**	**Diagnostic criteria**	**Unit**
X1	Surface geology	Resistance of the surface rocks to erosion and sediment yield		Surface geology types	class
X2	Soils	Resistance of the soil against erosion	soil texture, the resistance of particles, lime stone, clay disperse and primary humidity of soil;	Soil texture	class
X3	Climate	Aggressiveness of the rainfall to cause erosion		Rainfall erosivity (to be derived from rainfall amount)	Value of R
X4	Runoff	Potential of runoff generation		Hydrologic soil group classes	
X5	Topography	Contribution of topography for runoff generation and erosion processes		Slope	class
X6	Ground cover	Availability of covering material on or above the surface of the ground against the effect of precipitation	Vegetation, litter, and rock fragments	Number of trees per hectare and abundance of coarse fragments	
X7	Land use	Type and intensity of use of the land by human (degree of natural vegetative cover removal) (degree of natural balance)			class
X8	Upland erosion	Existence and extent of rill, sheet and gully erosion		Observed erosion	class
X9	Channel erosion and sediment transport	Transport expectancy of the streams	Shape of the channel, flow duration, channel cross section, drainage density, channel gradient, and width-depth ratio		

Table 7.3. PSIAC factor ratings and degree of limitation [modified after PSIAC (1968)]

Land quality	Quantitative Ratings	Qualitative Ratings	Degree of limitation	Description of suitability classes
Surface geology (X1)	0	Low	Nil	(a) massive hard formations
	5	Moderate	Slight –to-moderate	(a) rocks of medium hardness, (b) moderately weathered, (c) moderately fractured
	10	High	Severe-to- very severe	(a) marine shales and related mudstones and siltstone
Soils (X2)	0	Low	Nil	(a) high percentage rock fragments, (b) aggregated clays, (c) high in organic matter
	5	Moderate	Slight –to-moderate	(a) medium texture, (b) occasional rock fragments, (c) caliche layers
	10	High	Severe-to- very severe	(a) fine texture, easily dispersed, saline–alkaline, high shrink–swell characteristics, (b) single grain silts and fine sands
Climate (X3)	0	Low	Nil	(a) humid climate with rainfall of low intensity, (b) precipitation in form of snow, (c) arid climate with low-intensity storms, (d) arid climate with rare convective storms
	5	Moderate	Slight –to-moderate	(a) storms of moderate duration and intensity, (b) infrequent convective storms
	10	High	Severe-to- very severe	(a) storms of several days duration with short periods of intense rainfall, (b) frequent intense convective storms, (c) freeze–thaw occurrence
Runoff (X4)	0	Low	Nil	(a) low peak flows, (b) low volume of runoff per unit area, (c) rare runoff events
	5	Moderate	Slight –to-moderate	(a) moderate peak flows, (b) moderate volume of flow per unit area
	10	High	Severe-to- very severe	(a) high peak flows, (b) large volume of flow per unit area
Topography (X5)	0	Low	Nil	(a) gentle upland slopes (<5%), (b) extensive alluvial planes
	10	Moderate	Slight –to-moderate	(a) Moderate upland slopes (<20%) (b) moderate floodplain development
	20	High	Severe-to- very severe	(a) steep upland slopes (>30%), high relief, little or no floodplain development
Ground cover (X6)	-10	Low	Nil	(a) completely protected by vegetation, rock fragments, litter; little opportunity for rainfall to reach erodible material
	0	Moderate	Slight –to-moderate	(a) cover <40%; noticeable litter, (b) if trees present understory not well developed
	10	High	Severe-to- very severe	(a) ground cover <20%, vegetation sparse, little or no litter, (b) no rock in surface soil
Land use (X7)	-10	Low	Nil	(a) no cultivation, (b) no recent logging, (c) low-intensity grazing
	0	Moderate	Slight –to-moderate	(a) <25% cultivated, (b) 50% or less recently logged, (c) <50% intensively grazed, (d) ordinary road and other construction
	10	High	Severe-to- very severe	(a) >50% cultivated, (b) almost all of the area intensively grazed, (c) all of area recently burned
Upland erosion (X8)	0	Low	Nil	(a) no apparent signs of erosion
	10	Moderate	Slight –to-moderate	(a) about 25% of the area characterized by rill and gully or landslide erosion, (b) wind erosion with deposition in stream channels
	25	High	Severe-to- very severe	(a) >50% of the area characterized by rill and gully or landslide erosion
Channel erosion and sediment transport (X9)	0	Low	Nil	(a) wide shallow channels with flat gradients, short flow duration (b) channels in massive rock, large boulders or well vegetated, (c) artificially controlled channels
	10	Moderate	Slight –to-moderate	(a) moderate flow depths medium flow duration with occasionally eroding banks or bed

7.4. Materials and methods

7.4.1. Parameterization of individual factors

7.4.1.1. Geology factor

There are nine geologic classes in the watershed as identified by MoWR (2010) with a scale of 1:250,000 and the factor ratings were done by professional judgment (Ayenew, 2011: personal communication) at Addis Ababa University, department of Earth Science. The rating values range from 0 to10 as recommended by the PSIAC model.

7.4.1.2. Soil factor

The soil factor rating was done based on available erodibility (K) values of the four major soil types in the watershed as conducted by MoWR (2008, 2009, and 2010). The factor rating values were computed by multiplying the K values by 16.67 as recommended by MPSIAC which is the modified version and intended to avoid subjectivity in scoring the sediment yield factors.

7.4.1.3. Climate factor

The most commonly used index of rainfall aggressiveness, which is shown to be significantly correlated with sediment yields in rivers, is the ratio p^2/P, where p is the highest mean monthly precipitation and P is the mean annual precipitation (Fournier, 1960). Morgan (1976) obtained significant correlation between p^2/P and drainage texture (defined as the number of first-order streams per unit area). In this study, the climatic factor rating was based on Fourier Index (FI) which computes rainfall erosivity based on maximum monthly rainfall amount and annual rainfall amount (*equation 7.1*).

$$FI = p^2/P \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.1)$$

Where p is the mean monthly rainfall of the wettest month and P is the mean annual rainfall.

7.4.1.4. Runoff factor

The runoff factor rating values were assigned to each of the 12 soil types of the watershed (*table 7.10*). As a procedure, the infiltration capacity of each soil types was measured in the field using double-ring infiltrometer (*figure 7.1*). The double-ring infiltrometer is a simple and routinely used instrument which is used to determine the infiltration rate of water into the soil. After presoaking of the test areas, the double-ring infiltrometer are established on a level surface. The larger ring has 60cm and the smaller one has 30cm with both depths of 25cm. The water drops within specified time limits are recorded. The cans are refilled after each reading. The drops that occur in the inner ring during the final period or the average stabilized rate, expressed as cm/hr represents the infiltration rate for that specific soil type.

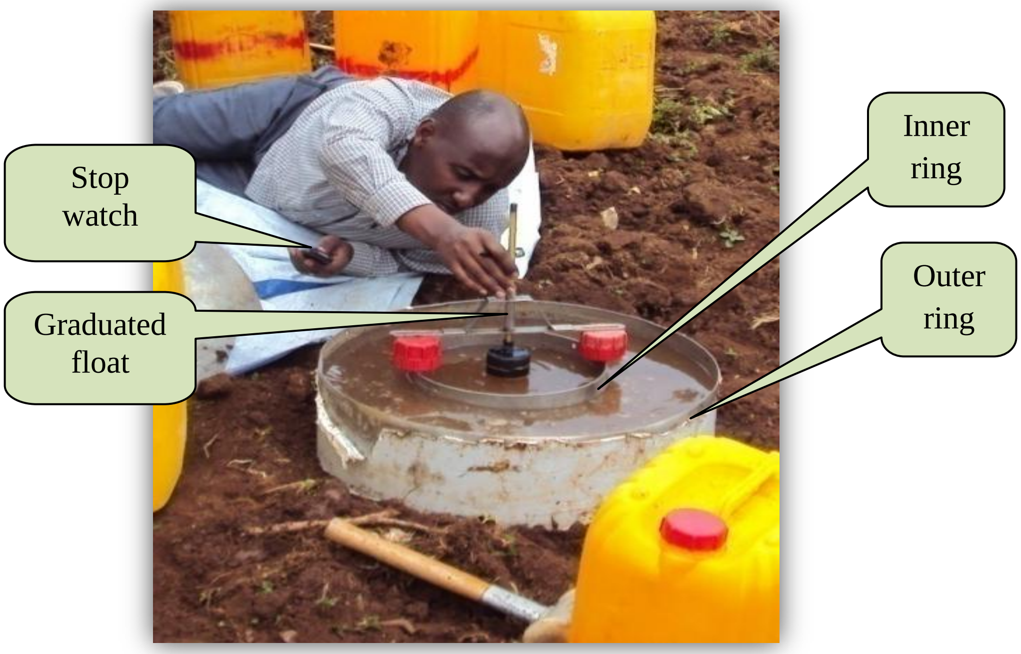


Figure 7.1. Field measurement of infiltration capacity using double-ring infiltrometer

7.4.1.5. Topographic factor

The topographic factor rating was computed from the SRTM Digital Elevation Model (DEM) with 30 x 30 m resolution. Values were assigned according to the revised PSIAC as shown in *table 7.4* below.

Table 7.4. Rating of topographic factor

(% Slope) = (Points)	
> 30= *20*	18-20= *10*
28-30= *19*	17-18= *9*
27-28= *18*	15-17= *8*
26-27= *17*	14-15= *7*
25-26= *16*	12-14= *6*
24-25= *15*	11-12= *5*
23-24= *14*	9-11= *4*
22-23= *13*	8-9= *3*
21-22= *12*	6-8= *2*
20-21= *11*	5-6= *1*
	< 5 = *0*

7.4.1.6. Land cover factor

The rating of land cover factor was done as recommended by MPSIAC which utilizes the percentage of bare land and computes the rating value by *equation 7.2*.

$$Y = 0.2X \qquad (7.2)$$

Where Y is vegetation cover factor value and X is bare soil (%)

The percentage of bare land is generated from VCF (Vegetation Continuous Fields) which is the product of MODIS (MODerate-resolution Imaging Spectroradiometer)(Hansen et al., 2002a, 2002b, 2003) and downloaded from NASA website. MODIS is an extensive program using sensors on two satellites where each provides complete daily coverage of the earth. The VCF collection contains proportional estimates for vegetation cover types: woody vegetation, herbaceous vegetation, and bare ground. The product was derived from all seven bands of the MODIS sensor onboard NASA's Terra satellite. This product is good for showing how much of a land cover such as "forest" or "grassland" exists anywhere on a land surface. The VCF product represents the total area of the watershed by 5432 cells with pixel resolution of 500m (*table 7.11*).

7.4.1.7. Land use factor

The land use factor rating was done in a similar manner with the land cover factor as *equation 7.3*.

$$\mathbf{Y7 = 20 - 0.2X7} \qquad (7.3)$$

Where Y7 is vegetation cover factor value and X7 is canopy cover (%)

The percentage of canopy cover was derived by merging the percentage of trees and herbs from VCF of MODIS (Hansen et al., 2002a; 2002b; 2003).

7.4.1.8. Upland erosion factor

The rating of upland erosion was done based on the type and degree of upland erosion. MoWR (2010) classified the entire watershed into three erosion zones as high, medium and low. The same classes are used in this study and the class with high rating assigned a rating value of 25, a value of 15 for the medium class and 5 points for the low potential parts of the watershed.

7.4.1.9. Channel erosion and sediment transport rating

This rating was done based on the spatial distribution of the drainage density in the watershed. This technique is adopted from Buoko and Mazurova, 1958 (*in* Stroosnijder and Eppink (1993)) in which an erosion class is attached to an elementary watershed depending on its drainage density (*table 7.5*).

Table 7.5. Erosion class based on drainage density (Buoko andMazurova, 1958 (*in* Stroosnijder andEppink (1993))

Class	Erosion Degree	Drainage density (km/km^2)	Rating value
1	Slight	< 0.1	2
2	Moderate	0.1 ≤0.5	4
3	High	0.5 ≤ 1.0	6
4	Severe	1.0 ≤ 2.0	8
5	Very severe	Greater or equal to 2	10

7.4.2. Arithmetic procedure for erosion/sediment risk assessment

The sediment yield index is the sum of values for the appropriate characteristics of each of the nine factors as shown in *table 7.6*. The final results are categorized into 5 classes as per the recommendation in the PSIAC model.

Table 7.6. PSIAC sediment classes

Rating	Sediment yield potential classes	Qualitative classifications
> 100	1	Very High potential
75 – 100	2	High Potential
50-75	3	Moderate potential
25-50	4	Low potential
0-25	5	Very low potential

7.5. Results and discussion

7.5.1. Result of surface geology rating

The result of the geology factor rating is shown in *table 7.7* and *figure 7.2* below.

Table 7.7. Rating of geological formations (from least to most susceptible for erosion)

Coding in map	Geological property	PSIAC Rating
1 Qwo	Obsidian and pitch stone	2
2 NQs	Nazreth group and dino formation, undifferentiated	3
3 Qwa	Rhyolitic and trachytic lava flows	4
4 Qdi	Ignimbrites, tuffs, water lain byroclatics, occasional lacustrine beds	5
5 N1_2n	Stratoid silicics: ignimbrites, unwelded tuffs, ash flows, rhyolites and trachytes	6
6 Qvs	Volcanic sedimentary rocks: lacustrine dominantly volcanoclastics sediments, tuffs	7
7 Qwpu	Pumice and unwelded tuffs	8
8 QI	Lacustrine sediments: sand, silt, pyroclastic sediments, diatomites	9
9 Qdp	Coarse unwelded pumicious pyroclastics	10

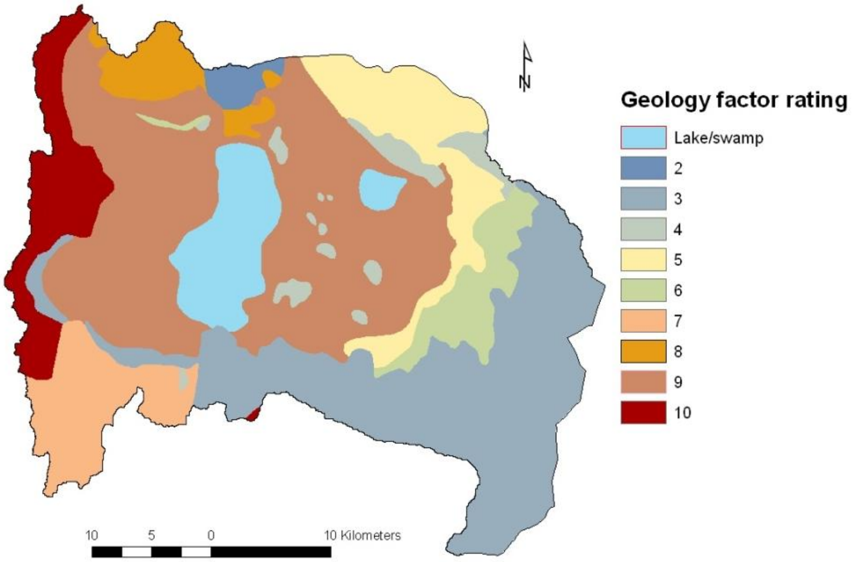


Figure 7.2. Spatial distribution of geology factor values

7.5.2. Soil rating result

As shown in *table 7.8* and *figure 7.3*, there are four major soil types in the watershed. These are Andosols, Cambisols, Luvisols and Leptosols with Nitisols and Regosols (MoWR 2008, 2009, and 2010). By adopting the recommendation of the modified PSIAC, the soil erodibility values (*table 7.8*) are multiplied by a factor of 16.67 to arrive at the soil rating values of each major soil.

Table 7.8. Soil rating of major soil types

Major soil type	K (USLE erodibility)	Rating value *(=16.67 K)*
Cambisols (CM)	0.13	2.17
Luvisols (LV)	0.11	1.8
Andosols (AN)	0.2	3.33
Leptosols (LP)	0.22	3.67

Source: MoWR (2010)

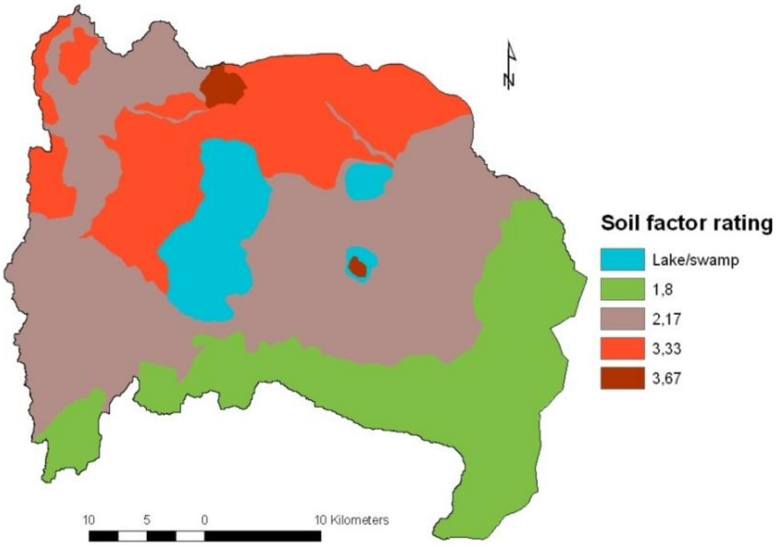


Figure 7.3. Spatial distribution of soil factor values

7.5.3. Climate rating result

Table 7.9 presents the coordinates, elevation, and long-term annual rainfall for the five meteorological stations in and around the watershed. *Figure 7.4* demonstrates how the Thiessen´s polygon delineates the respective area coverage of each station and the corresponding rating values of the climate factor.

Table 7.9. Spatial distribution of meteorological station within and near to the study area

	Station Name	X coordinate(m)	Y coordinate (m)	Elevation (m.a.s.l)	Mean Annual RF (mm)	Rainfall of wettest month (mm)	Fourier index	Climate rating value
1	Wendo Genet	456960	778399	1800	1151	150,80	19.8	6
2	Yirbaduwancho	433423	765478	2000	1120	155,10	21.5	7
3	Haisawita	451228	763012	2240	999	137,70	19	5
4	Hawassa	442235	779921	1750	953	124,10	16.2	2
5	Shashemene	455869	795581	1950	918	128,80	18.1	4

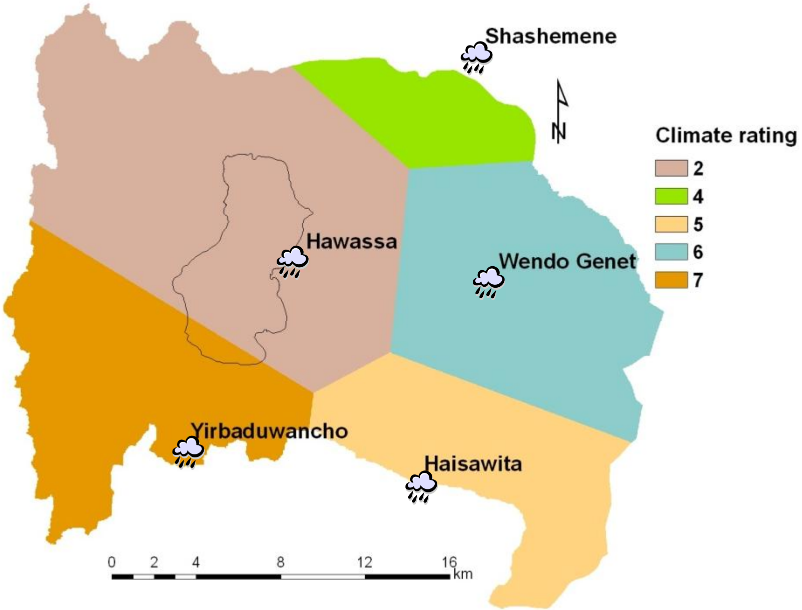


Figure 7.4. Location of meteorological stations and climate factor values

7.5.4. Runoff rating results

7.5.4.1. Results of Infiltration test

With the support of handheld PDA, which is installed with ArcPAD 10, each soil type (*table 2.1* in *chapter two*) was investigated for its infiltration capacity. Totally, 10 infiltration measurements are made in this study (measurement sites are shown in *figure 7.5*).

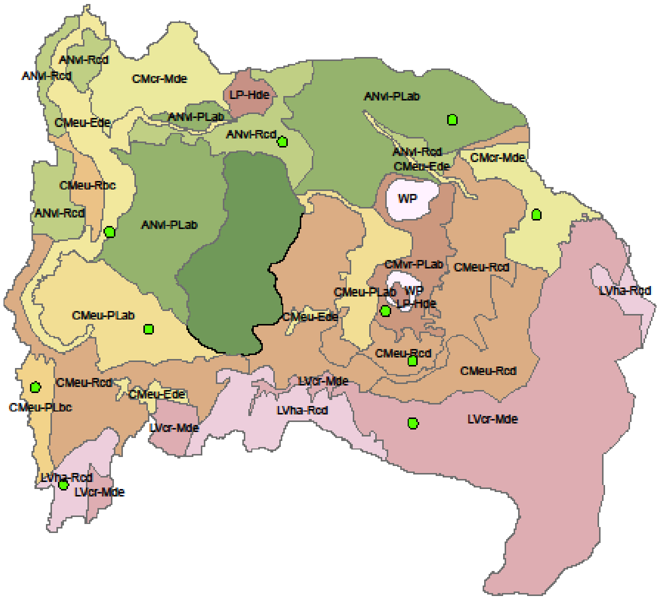


Figure 7.5. Locations of infiltration measurement sites

7.5.4.2. Rating of runoff potential from infiltration rate data

Based on infiltration rate values, each soil type was grouped into the corresponding hydrologic soil group (HSG) as shown in *table 7.10* below. The field assessment on the two soil types (CMeu-Rbc and LP-Hde) reveals that there exists water impermeable layer within 50 cm of the soil surface. According to the limits on the diagnostic physical characteristics of the hydrologic soil groups, both soil types are assigned to group D. The maximum value of 27 cm/hr was recorded on Andosols which is characterized by deep to very deep and mostly pumice below 40 cm. It may be the underlying pumice responsible to the high infiltration capacity in addition to its medium to coarse texture. The final rating is shown in *figure 7.6.*

Table 7.10. Rating of runoff factor

Soil type	Minimum infiltration rate (cm/hr)	Hydrologic soil group	PSIAC rating
LVcr-Mde	18	A	1
CMeu-Ede	12	B	4
CMeu-Rcd	7	B	4
LVha-Rcd	6	B	4
CMeu-PLab	5	B	4
CMeu-PLbc	9	B	4
ANvi-PLab	27	A	0
CMcr-Mde	6	B	4
ANvi-Rcd	15	A	1
CMvr-PLab	3	C	7
CMeu-Rbc	Very shallow	D	10
LP-Hde	Very shallow	D	10

[Source: Findings of field measurement]

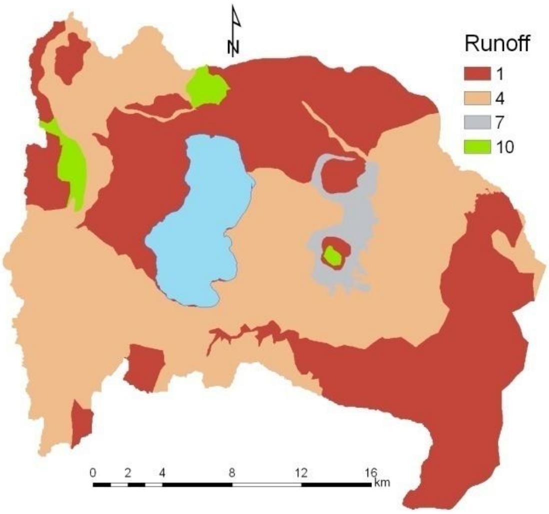


Figure 7.6. Distribution of hydrologic soil groups in the watershed

7.5.5. Topography rating result

The rating of topographic factor was done as shown in *table 7.4*. *Figure 7.7* shows the final rating.

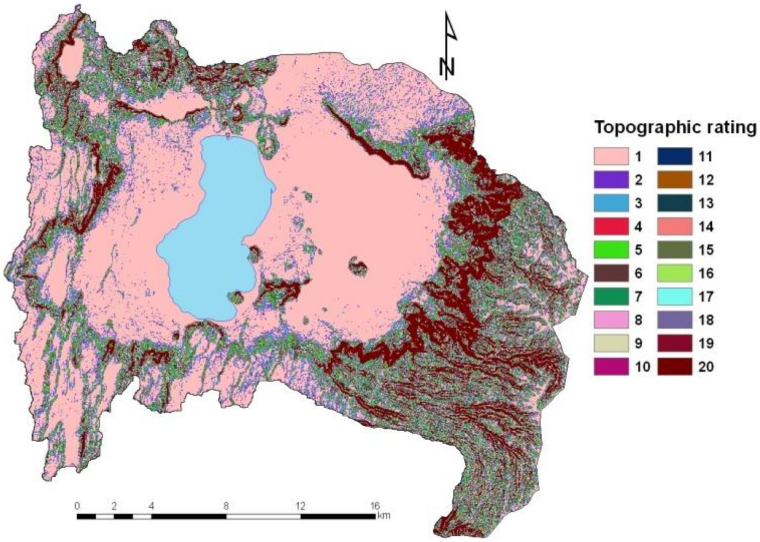


Figure 7.7. Rating of topographic factor based on slope percentage

7.5.6. Land cover rating result

7.5.6.1. Extracting percentage of bare land for each land cover type

The available land cover types of MoWR (2010) was used in combination with the Vegetation Continuous Fields (VCF) of Hansen et al. (2002a; 2002b; 2003). The land cover types were used as classification units and the average percentages of bare land (*figure 7.8*) were extracted from VCF using ArcInfo tools as shown in *table 7.11*.

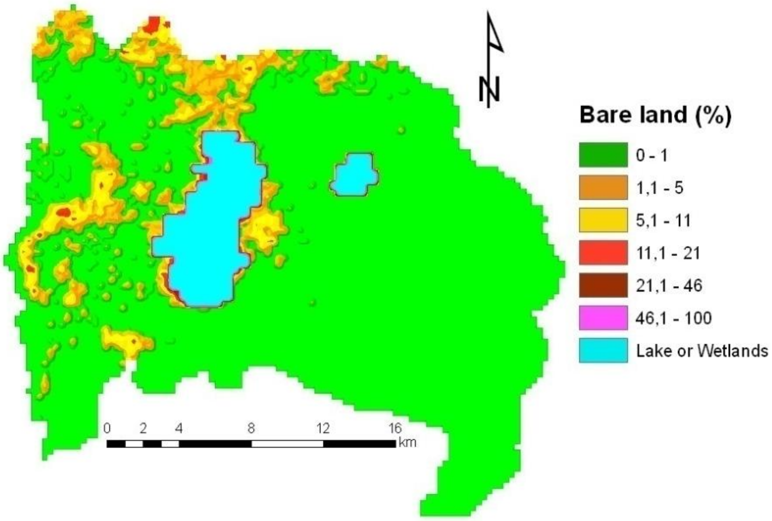


Figure 7.8. Derivation of bare land percentage from Continuous Fields (VCF) (with 500m grids)

Table 7.11. Percentage of bare land in each land cover type (500m resolution)

	Land cover type (Code)	Count	Mean % of bare land	Land cover rating value (= 0.2X6)
1	Open shrubland (SO)	355	1.5	0.3
2	CI2	45	0	0
3	Intensive Mechanized Cultivation (State) (CIMS)	142	2	0.4
4	Plantation forests (FP)	54	0.9	0.2
5	Open grassland (GO)	259	4.4	0.9
6	Open grassland /Open woodland (GO/WO)	135	0	0
7	Lake	392	-	-
8	Dense Shrubland (SD)	92	5.9	1.2
9	Urban or Built-Up Areas (U)	177	3.3	0.7
10	Intensive smallholders cultivation (CI3)	2468	0.7	0.1
11	Marshland (MA)	295	33.5	6.7
12	Open grassland with moderate smallholder cultivation (CM3/GO)	141	0.2	0.04
13	Intensive smallholders cultivation (CI4)	1134	1.6	0.3
14	Disturbed High Forest (FD)	119	0	0

7.5.6.2. Land cover rating from percentage of bare land

The final rating of land cover factor was computed through *equation 7.2* as shown in *figure 7.9* below.

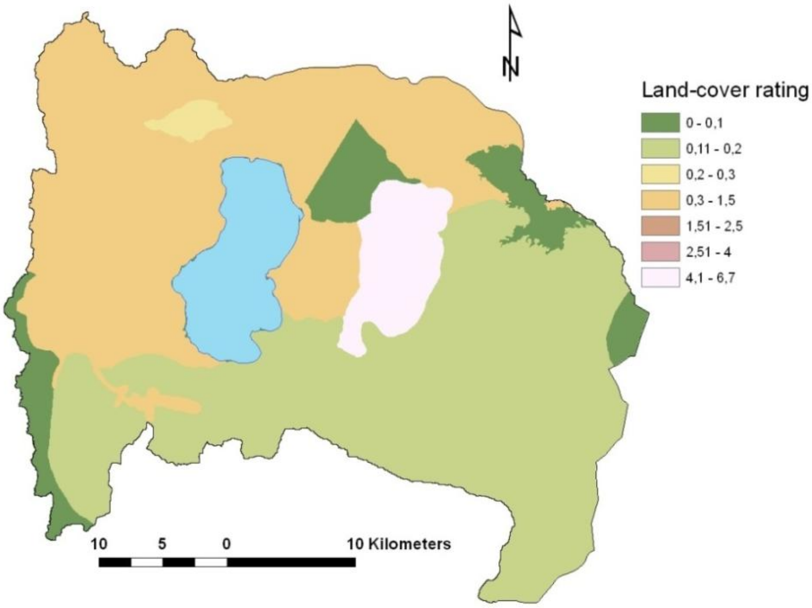


Figure 7.9. Rating of land cover factor

7.5.7. Land use rating result

7.5.7.1. Extracting percentage of canopy for each land use types

VCF was produced for percentage bare soil, percentage of herbs and percentage of trees which constitute 100% of the entire area (*figures 7.8 and 7.10*).

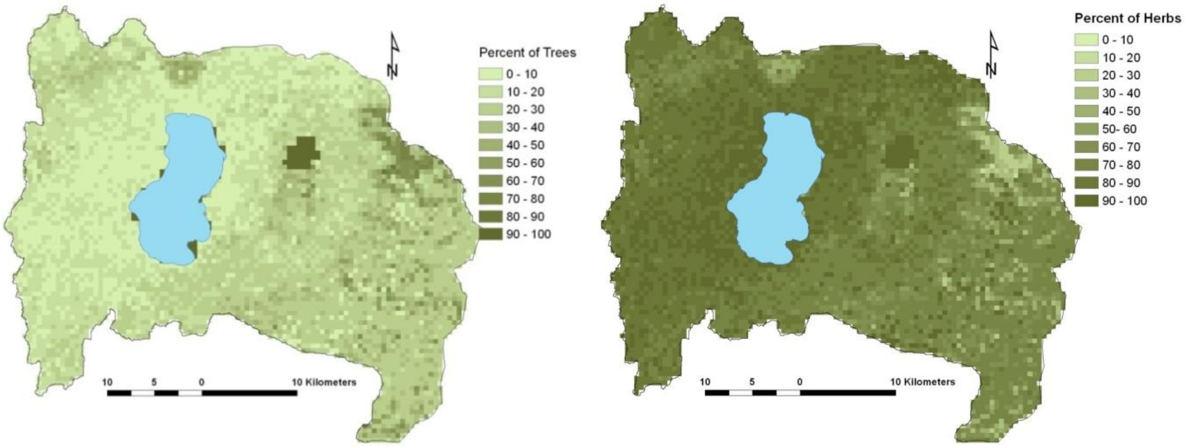


Figure 7.10. Derivation of tree percentage from Vegetation Continuous Fields (VCF)

For the rating of land use factor, the percentage of herbs and trees were added up to give canopy percentage (*figure 7.11*).

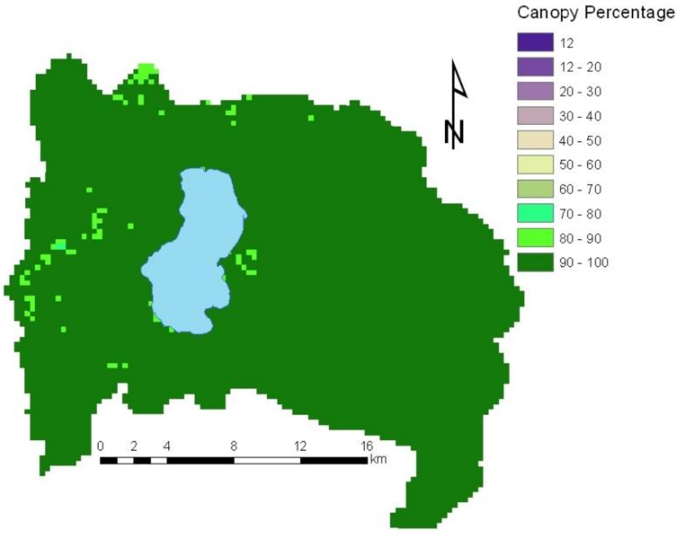


Figure 7.11. Percentage of canopy cover computed from MODIS satellite data

The average percentage of canopy was extracted for each land use types MoWR (2010) as shown in *table 7.12*.

Table 7.12. Percentage of canopy in each land use type (500m resolution)

	Land use type (Code)	Count	Mean % of tree (T)	Mean % of herbs (H)	Total canopy %) (X7= T+H)	Land use rating value (= 20 - 0.2X7)
1	GB(FP)	507	17.3	82.4	99.7	0.06
2	Intensively cultivated land (IAC)	608	10	90	100	0
3	Intensively cultivated land (IAC)	54	7.8	91.9	99.7	0.06
4	Intensively cultivated land (IAC)	88	10	90	100	0
5	TMFP	54	11	88.1	99.1	0.18
6	Grassland (G)	33	9.3	86	95.3	0.94
7	Grassland (G)	204	10	86.3	96.3	0.74
8	Grassland (G)	22	4.9	84.6	89.5	2.1
9	Lake WSFR(NC)	392	-	-	-	-
10	GB(FP)	75	30	66.2	96.2	0.76
11	Urban (RCI)	177	13.1 (bare=3.34)	87.2	96.66	0.67
12	IPAC	2468	25	75	100	0
13	Swamp area (DGF(NC))	295	0	96.8	96.8	1
14	MPAC(L)	141	13.2	86.6	99.8	0.04
15	Intensively cultivated land (IAC)	571	14.7	84.7	99.4	0.12
16	TM(NC)	119	54.8	45.2	100	0

7.5.7.2. Land use factor rating from percentage of canopy cover

Based on *equation 7.3*, the final rating of land use factor was computed as shown in *figure 7.12.*

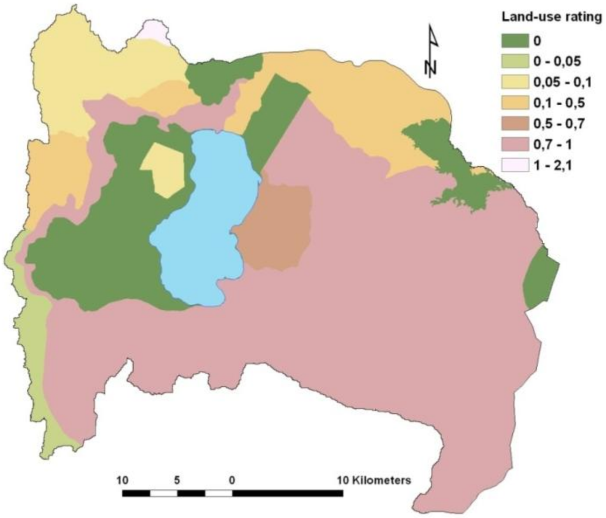


Figure 7.12. Rating of land use factor

7.5.8. Upland slope erosion rating result

MoWR (2008, 2009, and 2010) assessed upland erosion in the watershed based on types and degree of erosion. This study categorized the entire watershed into three qualitative erosion classes as "severe", "medium" and "slight". The same erosion classes are used in this study. Following the recommendation of PSIAC model to assign the value of 25 for the worst case, the areas which had been classed as "severe" were assigned to have a value 25. The remaining "medium" and "slight" classes proportionally assigned values of 15 and 5 respectively as shown in *figure 7.13*.

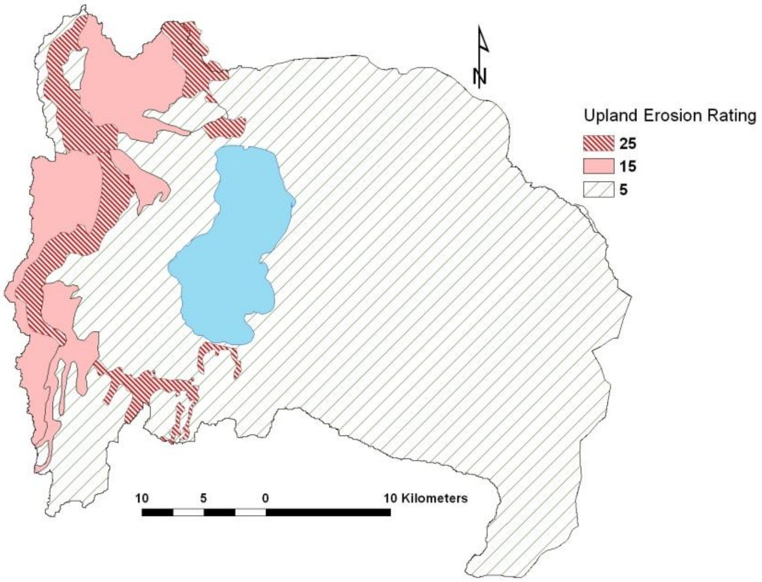


Figure 7.13. Upland land erosion rating

7.5.9. Channel erosion and sediment transport rating result

This factor was rated based on the available drainage network as identified by MoWR (2008, 2009, and 2010) and the corresponding density classes were adopted from Buoko and Mazurova (1958) (*cited in* Stroosnijder and Eppink, 1993) as shown in *table 7.5*. Based on the line density calculation tool of ArcGIS10, the final rating was done as shown in *figure 7.14.*

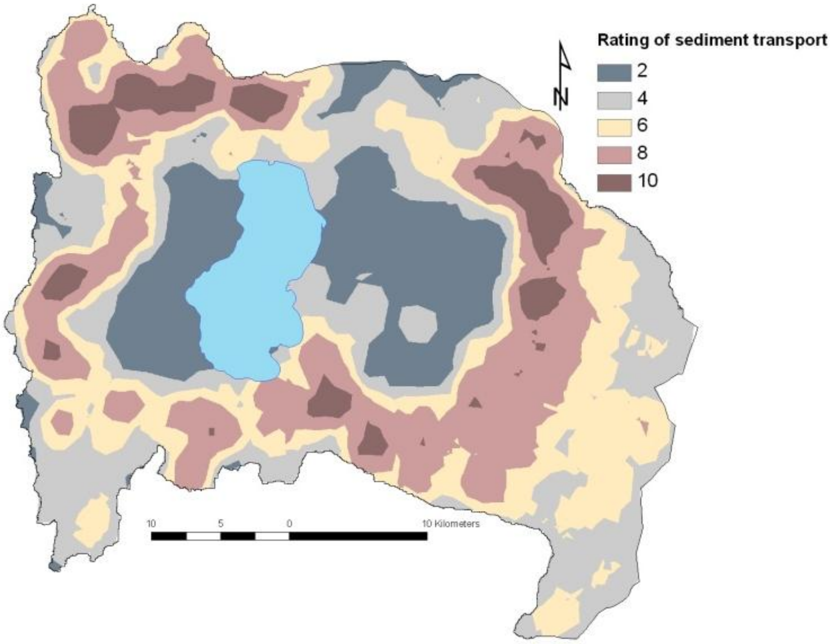


Figure 7.14. Sediment transport rating

7.5.10. Identification of erosion/sediment source areas: the model output

The final identification of the erosion/sediment source areas was made by overlaying the ratings of the nine factors using the "model run" option of ArcGIS10 as shown in *figure 7.15*.

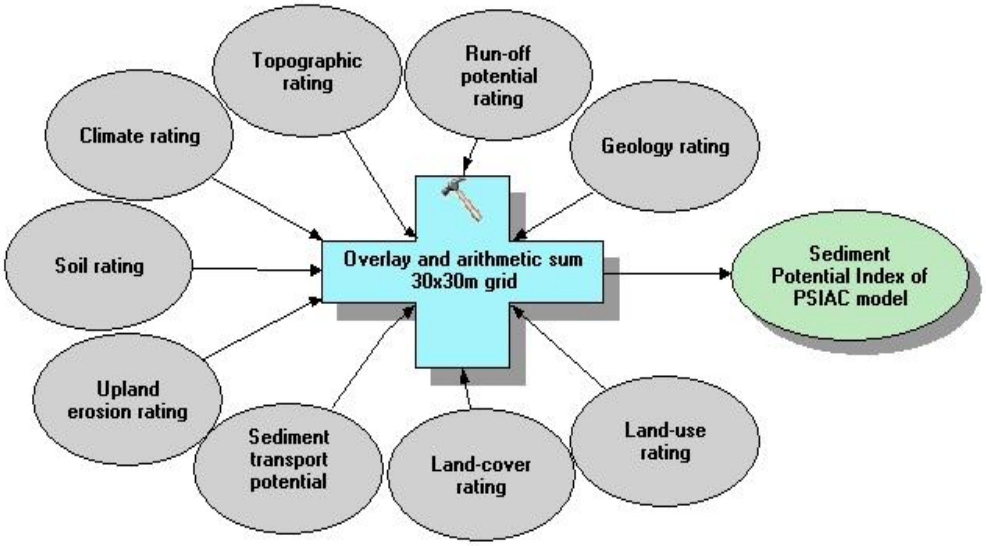


Figure 7.15. Output diagram of model builder after running the raster input data by ArcGIS10

The final output of the modeling process is presented in *figure 7.16* and *table 7.13* below. According to the model result, 66.4% of the watershed area is found to be classed as "low potential"; 22.7% under "very low potential"; 10.6% "moderate potential" and only 0.3% is under "high potential" and none of the watershed area is categorized as "very high potential".

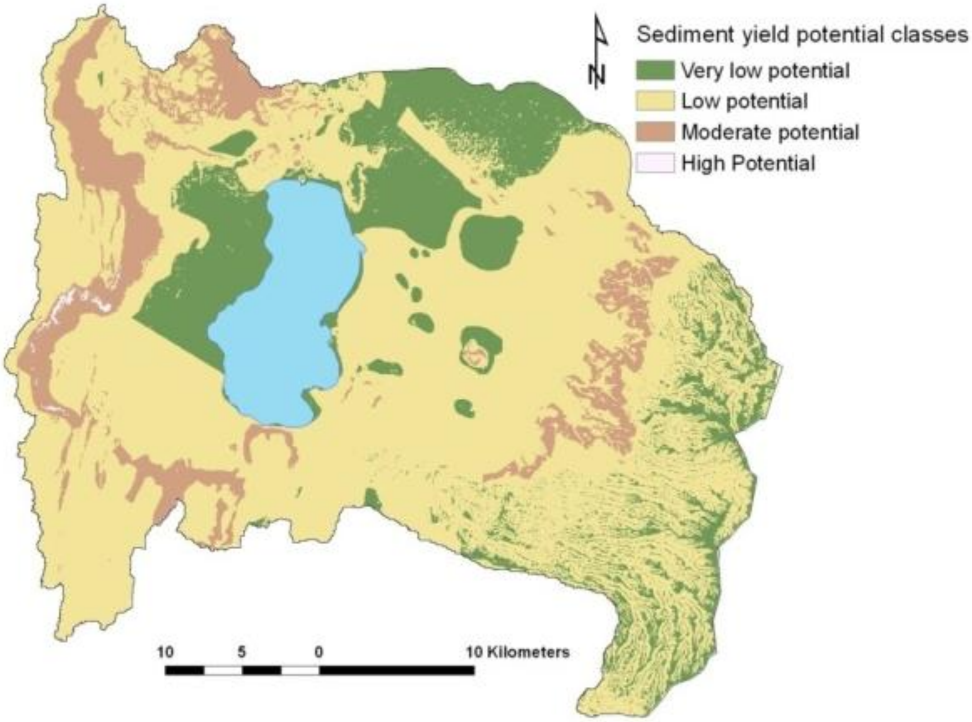


Figure 7.16. Spatial distribution of sediment yield potential classes in the watershed

Table 7.13. Percentages of each potential classes

Sediment class	Qualitative categories	PSIAC value	Q_s (Sediment yield = total volume of sediment /sediment producing area) ($m^3/km^2/yr$)	% of the watershed area
5	Very high Potential	>100	>1450	0
4	High Potential	75-100	450-1450	0.3
3	Moderate potential	50-75	250-450	10.6
2	Low potential	25-50	95-250	66.4
1	Very low potential	<25	< 95	22.7

The overall result of sediment source identification shows that the distribution of sediment sources in the watershed is disproportionate and two distinct patterns are distinctly identified by the model in the Western and Eastern parts of the watershed. Regarding the western part, the high erosion rate and the coinciding high drainage density (as shown in *figure 7.14*); sensitive geological formation (as shown in *figure 7.2*); high gully density (as shown in *figure 6.4*); and higher percentage of bare land (as shown in *figure 7.8*) seem to make this part of the watershed to be the principal sediment source. But, the Eastern part seems to be influenced by its topography (very steep slope) (as shown in *figure 7.7*) and high drainage density (as shown in *figure 7.14*). This part is the likely source of sediment that silted up in Lake Cheleleka.

7.5.11. Comparison of sediment yield estimation to previous studies

To validate the accuracy of prioritization, some measured data are required but such data are not available. In the current situation of data availability, testing for the prediction capacity of the PSIAC model cannot be undertaken, and also not intended. However, comparing the outputs with other studies offers some clue on the general and crude performance of the model. In this case, the output of PSIAC model is compared with the estimation in-lake sedimentation of *chapter 6* and the Annualized Agricultural Non-point Sources (AnnAGNPS) model output as studied by Shamo (2008). Individual outputs are shown in *table 7.14* below.

Table 7.14. Summary of model outputs

	Estimated Sediment yield	Annual values of erosion and/or sediment yield	Sources
1	PSIAC	95-250 $m^3/km^2/yr$ (66.4 % of watershed area) and <95 $m^3/km^2/yr$ (22.7 % of watershed area)	Own study (chapter 7)
2	Hydrographic survey	967 $m^3/km^2/year$ (long-term average)	Own study (chapter 6)
3	Ann-AGNPS	< 1 mm/ha/yr (most part of the watershed) or <1000 $m^3/km^2/yr$	Shamo (2008)

The magnitude of specific sediment as computed in *chapter 6* is 967 m^3/km^2/year. In this case, sediment contributing area is considered by deducting the surface area of the lake (about 93.24 km^2) and the two closed sub-watershed: Muleti = 91.6 km^2, and Wondo Kosha= 114 km^2) from the total watershed area (1436.5 km^2). Whereas the PSIAC model estimates this parameter as to fall between 95-250 $m^3/km^2/yr$ (66.4 % of the watershed area) and < 95 $m^3/km^2/yr$ (22.7 %). Shamo (2008), who employed the AnnAGNPS model reported that most of the area of the watershed has sediment yield of less than 1 mm/ha/yr (1000 m^3/km^2/year).

As shown in the above comparisons, the results of the hydrographic technique and AnnAGNPS can be considered as fairly similar, but the PSIAC estimation is considerably lower than the former results. The accuracy of all the three methods can be evaluated only if actual sediment flow from the watershed has been monitored. For the moment, it is thinkable that result of the hydrographic survey is better because of the fact that it is the result of direct measurement and comparison of two bathymetric maps.

7.6. Conclusion

This study targets the identification of critical sediment source areas in Lake Hawassa watershed using PSIAC model. The model screens the hot-spots and the results are in good agreement with field verifications and justify its sufficiency in achieving the objective as a screening model. The final product remains qualitative because of the absence of measured data to validate the method. On the basis of our results, the watershed area is classified into four sediment yield classes (high, moderate, low, and very low potentials).

The model is open in nature and can accommodate more number of factors as far as it influences the erosion and sedimentation process in the watershed. Such opportunity paves a way for future adoption of the model by including new inputs. The subjectivity of parameterization and final result deserve a special care. Moreover, the model shall be quantitatively validated for its maximum benefit. The result of this study can be used for watershed prioritization that is an inevitable part of watershed management which embodies reduction of sediment deliveries into the lake.

Chapter 8. Participatory assessment of anthropogenic factors affecting the hydrology of Lake Hawassa: an application of DPSIR framework

8.1. Introduction

The list of environmental issues has been growing and their inter-linkages with their complex causes and consequences are getting complex. To tell an integrated story of these issues, the need of structured process (framework) that can accommodate interdisciplinary knowledge is of a paramount importance (UNEP, 2008). In recent years, most of environmental assessment studies are based on the casual chain frameworks (e.g. Pressure-State-Response (PSR), Driving force-State-Response (DSR), and Driving force-Pressure-State-Impact-Response (DPSIR)). These frameworks have made an important contribution by emphasizing the importance of causality (Niemeijer and Groot, 2008).

DPSIR (*pronounced dipsir*), as one of the conceptual tools, helps to identify and describe processes and interactions in human-environmental systems (Burkhard and Mueller, 2008). It has a potential to link the existing data, gathered from various previous studies, in causal relationship (Sekovski et al., 2012). As different cause and effect chains are included in the model and because it is intended as an iterative loop, the model is adaptive to arising changes and developments.

The DPSIR framework is an extension of the Pressure-State-Response (PSR) model, developed by Anthony Friend in the 1970s, and subsequently adopted by the Organization for Economic Cooperation and Development (OECD). It was developed for reporting purpose and structures the description of the environmental problems by formalizing the relationships between various sectors of human activity and the environment as causal chains of links. *Figure 8.1* presents the meaning of the DPSIR elements.

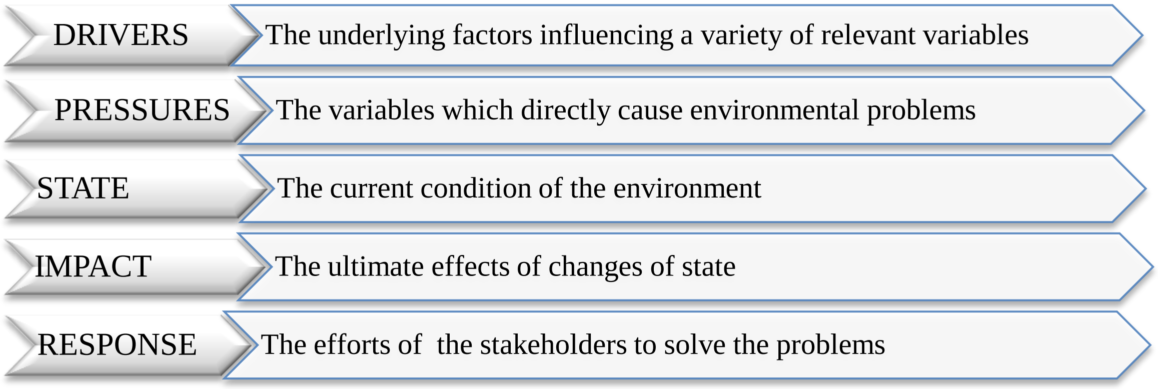


Figure 8.1. Terminology of DPSIR model [Source: modified after EEA (1999; 2000).

By definition, DPSIR model is considered as the best way to structure environmental information providing environmental socioeconomic integrity - in order to build links between natural and socio-economic sciences; science and management; qualitative and quantitative analyses; measured and modeled data; and definition of environmental syndromes (Turner et al., 1998; EEA, 2003). Since its conception, the framework has increasingly been applied in research projects with the aim of supporting decision making. A number of attributes of the framework regarding structuring and communication issues in research further strengthen its original purpose of bridging the science-policy gap (Tscherning et al., 2011). The full-fledged causal chain from driving forces to impacts and responses is a complex task, and tends to be broken down into sub-tasks, e.g. by considering the pressure-state relationship (Kristensen, 2004).

The previous chapters furnished the bio-physical information of the hydro-system and we know less about the associated socio-economic challenges that are often the causes of many biophysical challenges (Gregersen et al., 2007). *Chapter four* and *five* were devoted to the assessment of hydro-climatic factors and *chapter six* showed the rate and magnitude of sedimentation in the lake. Some of these variabilities are the result of a complex interplay between natural and anthropogenic factors.

This chapter is intended to create a platform on which the cause-effect chain of anthropogenic factors can be viewed in an integrated manner. It considers the management of Lake Hawassa as synonymous with the "response"; and the current hydrological status of the lake as "state".

D and P are considered to cause the current status of the lake. *Figure 8.2* shows how the DPSIR framework used in a decisional context.

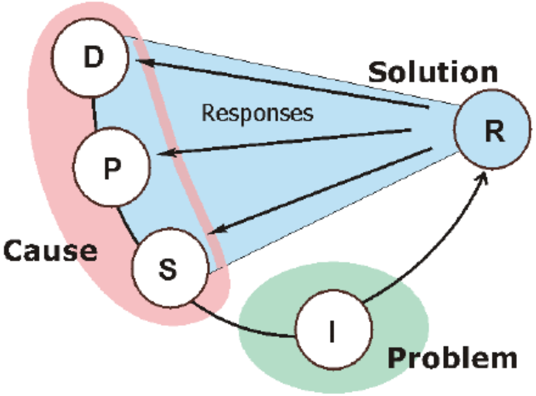


Figure 8.2. The DPSIR framework in a decisional context [Source: Vázquez, 2003)]

8.2. Objectives of the chapter

The objectives of this chapter are dual. On one hand, the perception of stakeholders about the likely anthropogenic causes that affect the hydrology of Lake Hawassa is assessed. On the other hand, the findings of previous studies are assembled in the DPSIR framework so as to build an integrated story that tells "how the lake hydrologically operates".

8.3. Methodology

8.3.1. General methodology

Figure 8.3 presents the flow chart of the general methodology in which the process starts with identifying the stakeholders followed by contacting them as individual or group. Focus group discussions and individual interviews were the two main techniques employed. After building a common understanding on the existing cause-effect links, the participants were encouraged to fill the DPSIR story sheets (*figure 8.4).* The results then cross-checked and supplemented by secondary sources.

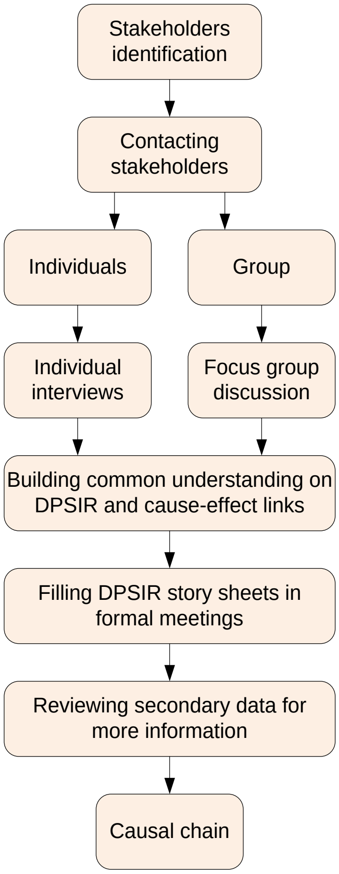


Figure 8.3. Flowchart for causal chain assessment of anthropogenic factors

8.3.2. DPSIR story sheet and participatory approach

The more detailed information was collected during the focus-group discussions (Cameron, 2000) which were conducted with participants (representing stakeholders) who have good familiarity with the topics and the study area. To give everyone the opportunity to express her/his opinion, six to eight people participated in each focus group. A total of five focus group discussions were conducted in this study. The participants were encouraged to fill the DPSIR story sheet (*figure 8.4*). Other participatory methods which were used as community truthing include (i) key informant interviews (Hay, 2004), and (ii) participants observations (Cook, 1997). Those "experts" who were identified by local people as having special knowledge (Warburton and Martin, 1999) were also interviewed.

Once the participants of the focus group discussions were, they were oriented about the concept of DPSIR chain and provided with two DPSIR story sheets (*figure 8.4*) to write the most likely cause-effect chains as per their own perception. The two main issues/topics in the cause-effect chain were: lake level rise and lake sedimentation. The participants were encouraged to talk openly and discuss the issues with other members and state their opinion before filling the sheets. Due to the absence of incentives, the time of discussion was deliberately reduced.

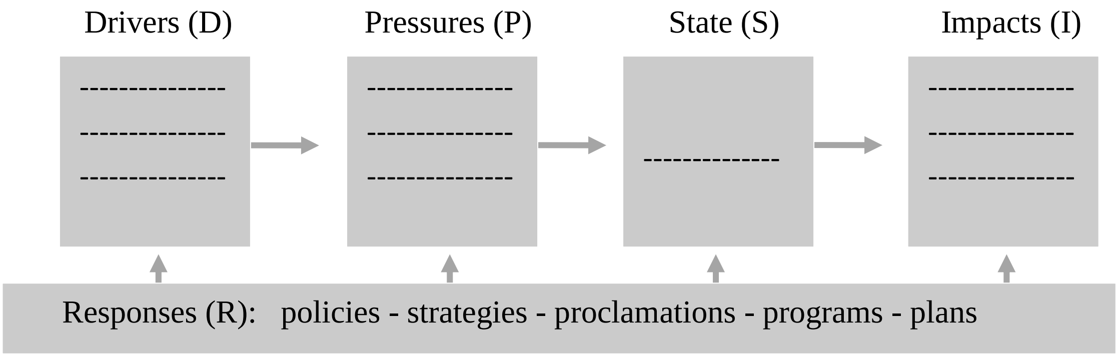


Figure 8.4. Template of DPSIR story sheet

8.4. Results and discussion

8.4.1. "Indirect drivers" (iD)

This study identified the need for one more component to the original DPSIR which helps to explain causes of the drivers (D) and can be viewed as a variation to the framework. This additional component is named as "indirect driver" and abbreviated as "iD" as shown in *figure 8.5* below. Similar naming was used by Maxim et al.(2009).

The perceived principal indirect drivers/root causes underlying the causal-chain affecting the hydrology of Lake Hawassa are found to include: population growth and density, agricultural development, the use of wood as primary source of energy, socio-political changes, and the existing land tenure system (*figure 8.5*). The upcoming sub-sections discuss the individual issues in detail.

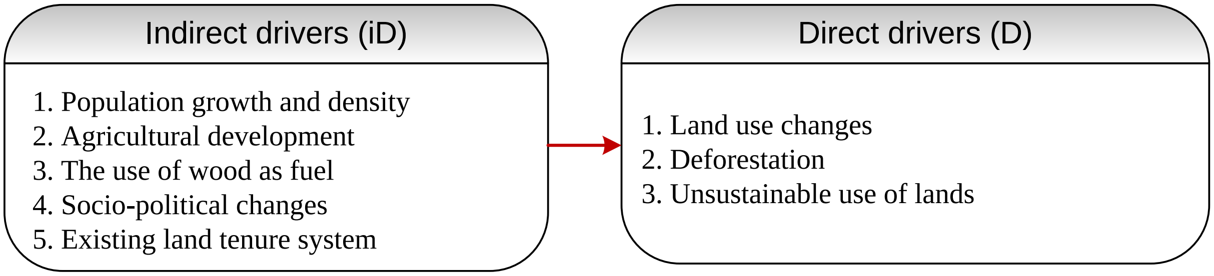


Figure 8.5. Primary and secondary driving forces affecting the hydrology of the system

8.4.1.1. Population growth and density

Demographics of the watershed communities, as one of the root cause in the causal chain was also perceived by Esayas (2010), MoWR (2008), Dessie (2004), WWDSE (2001), Shewangizaw and Michael (2010) and many others. Having 2005 as base year, the population of the watershed is estimated to be 621,530 people. This is expected to double before 2025, and grow to nearly 1.6 million by 2035 at an average growth rate of 3.15%, but with a higher rate of 3.8% in the early years to 2010 (*table 8.1*). Population density of the watershed is estimated as 624 people/km^2 (MoWR, 2008) which is unusually high and about eight fold of the average value at country level, that is about 77.72 people/km^2 (World Bank, 2012).

The livestock population is also additional stress which constitutes 516,159 cattle, 95,035 sheep, 95,035 goats, 12,763 horses, 28,912 donkeys and 486 mules. The livestock density is calculated as 335 TLU/km^2 (MoWR, 2008). [TLU = tropical livestock unit; for example: 1 TLU = Camels 1.0, Cattle 0.7, Sheep/Goats: 0.1 (FAO, 2005)]. The impacts of population growth are also being felt in the watershed with population pressure impacting many of the other issues such as deforestation, land degradation, overgrazing, and increasing food insecurity.

Table 8.1. Population growth in seven administrative units in and around the watershed

Place	2005			2010	2015	2020	2025	2030	2035
	Total	Male	Female	Population	Population	Population	Population	Population	Population
ArbeGona	12,971	6,521	6,451	15,590	18,479	21,621	25,080	28,931	33,128
Hawassa	430,664	219,536	211,127	517,622	613,539	717,857	832,725	960,610	1,099,952
Shebedino	77,594	39,428	38,165	93,261	110,542	129,337	150,032	173,073	198,178
Siraro	1,811	888	924	2,241	2,695	3,142	3,614	4,167	4,790
Kofele	8,553	4,242	4,311	10,583	12,728	14,840	17,067	19,679	22,623
Shalla	15,748	7,717	8,031	19,485	23,433	27,320	31,421	36,229	41,647
Shashemene	74,190	36,836	37,354	91,802	110,410	128,725	148,048	170,708	196,238

[Source: MoWR (2008)]

8.4.1.2. Expansion of agriculture

This perception of the stakeholders is also supported by Dessie (2004), Esayas (2010) and others. According to these sources, expansion of agriculture in particular smallholder farming, contributes to over 80% of the forest area loss. This expansion is characterized by two major modes of change: 1) internal: clearings created by the intrusion of small farm plots, grazing lands, and villages 2) external: expansion of agriculture from the exterior into the forests. Generally, the changes from natural vegetation to cultivation as depicted by *figure 8.6* indicates that agricultural expansion in the watershed is the most important proximate cause of land use change and it takes place at the expense of other land uses.

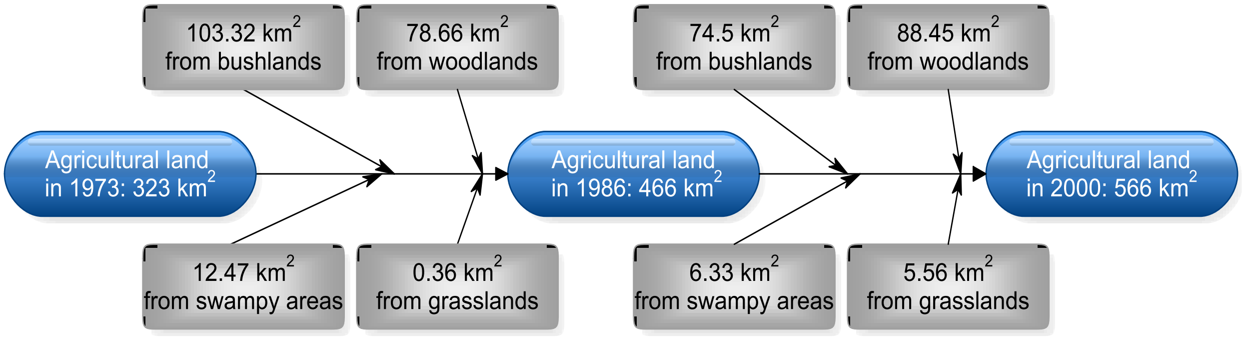


Figure 8.6. Trends of agricultural land expansion in the watershed [Source of raw data: Abrha (2007)]

8.4.1.3. The use of "wood" as energy source and absence of alternative energy

Fuel woods supplies 84% of total energy demands of which about 50% is from shrub-lands and wood-lands (exceeding their mean annual increment of woody biomass) and only 5-10% is from woodlots with the remainder from crop residues and dung (MoWR, 2008). Household energy requirements are supplied largely by fuel wood collected from existing woodland and shrub land, maize straw, and charcoal with cow dung also used in the western part of the watershed. The use of biomass accelerates the rate of deforestation and erosion while the use of crop residues and dung as fuel, rather than returning this organic matter to the soil, causes a decline in soil fertility and deterioration in soil structure.

8.4.1.4. Socio-political changes

Ethiopia has witnessed several dramatic political changes during the course of the last century. These changes have been accompanied by transitional periods characterized by uncertainty and insecurity. In the absence of firm political control, control of resources has also been lacking. Many among the rural population have then taken the opportunity to usurp what has been available in terms of, for instance, forest land and forest products, adding to the process of forest decline (Dessie, 2004; Dessie and Christiansson, 2008).

8.4.1.5. Land tenure system

All lands in Ethiopia are nationalized and redistributed in 1975. This policy has continued with the present Government and the 1994 Constitution specifies that land cannot be subject to sale or exchange (FAO, 2004). Issues of land tenure could include insecurity of tenure, ability to use land as collateral and the transferability of property rights and the impacts these have on land investment or factor (land, labor or capital) allocation. A major source of tenure insecurity emanates from the periodic land redistribution to land-poor households (Mahmud Joseph and Pender, 2005). This indirect driver is also identified by MoWR (2010). Currently, the government is implementing a land certification programme that is expected to reduce the effect of land insecurity among the land users but its effectiveness is not yet evaluated.

8.4.2. "Direct drivers" (D)

8.4.2.1. Deforestation, land use and land cover changes

As perceived by the stakeholders, expansion of agriculture and population growth are the two main causes for the land use changes in the watershed. The magnitudes of land use changes were attempted to be addressed by different studies, such as Wagesho et al. (2012) and Abrha (2007) for the period of 1973, 1986, and 2000 at the watershed scale (*table 4.3* in *chapter four*). Ayenew et al. (2007) also stated that the land use changes in the watershed affected the hydrology of the lake. While assessing the causes of these land use changes, Legesse et al. (2003) noted that they are resulted from multiple forces such as: demographic trends, climate variability, national policies, and macroeconomic activities.

The watershed has also undergone progressive deforestation (Lamb et al., 2002) and the results of interview and individual/group discussions also reveal that "deforestation" is one of the direct drivers which is perceived to be caused by the use of "wood" as source of energy for cooking (its impact is also exaggerated by the absence of alternative energy); socio-political changes especially during the period of political transitions; and agricultural expansions. Similar causal chain was reported by Dessie (2004) which adds the economic activities and local conflicts over resources to play an important role. According to Dessie (2004), the total natural forest loss between 1972 and 2000 amounted to over 40,000 ha, which is over 80 % of the forest cover that was present in 1972. This corresponds to an annual loss of over 1400 ha, equivalent to 0.9% of the annual national loss. The decreasing trend of forest coverage in the study area coincides with the general forest decline pattern in Ethiopia. The forest decline during this period was not an isolated event, but rather a continuation of the past trend. Esayas (2010) also mentioned that forest clearing exerted pressures on the natural resources of the watershed.

During field visit, it was also observed that forests which were owned by the community were depleting which might be explained by the lower regard for common property and common access land than for individual holdings. Woodlands are also depleted which seems to be driven by the demand for fuel wood and charcoal. There are few remnants of trees seen in the Western side of the lake. These remnants are preserved against cutting due to few influential community members who created awareness among their neighbors, and now these trees are taken as symbols of environmental protection.

8.4.2.3. Unsustainable use of lands

Farmers seem to lack the commitment to implement and maintain the already implemented measures. Previously constructed soil and water conservation works are also destroyed or abandoned in many places in the watershed due to the lack of maintenance. Such reluctance is perceived by the participants as to emanate from the existing land tenure system. Some justified that it could be due to the lack of communal understanding on the importance of these measures and lack of land management enforcement. Cultivation of steep slopes is also one of the common misuses of the lands in the watershed.

8.4.3. "Pressures" (P)

The "pressure" component in this study constitutes the input of water and sediment to the lake that potentially affect the hydrological status of the lake.

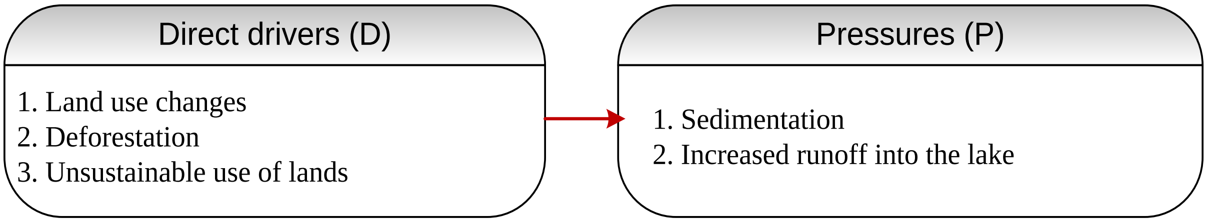


Figure 8.7. Link between direct drivers and pressures

8.4.3.1. Sedimentation

In *chapter 6*, it was shown that the thickness of accumulated sediment in the lake between 1999 and 2010 was about 14 ± 5cm (*figure 6.3*). If a constant annual rate is assumed, the sedimentation rate would be 1.2 cm/year and it can be considered as a pressure and part of the causal chain. Soil erosion and sedimentation can be influenced by both climate and anthropogenic factors and differentiation between them is recommended.

8.4.3.2. Increased runoff from the watershed

As discussed in *section 4.5.4* of *chapter four*, the runoff from Tikur Wuha River shows an increasing trend whereas rainfall has no significant changes. The role of anthropogenic factors (through land use/cover changes) can be deduced from the interplay between the trending runoff and non-trending rainfall.

8.4.4. "State" (S)

As a result of the factors that were described as pressures, the hydrology of Lake Hawassa has been changed as indicated in *chapter four* that was expressed in terms of its significant increasing trend (average annual rise of 4.9 cm/yr). As justified in *section 4.5.6* (*chapter four*), the anthropogenic factor has a stake atleast in modifying the impact of climate. This in turn contributes for the resultant rise of the lake level. The sequential regime shifts in the lake level series are less likely associated with human factors.

8.4.5. "Impact" (I)

The notable impact of Lake Hawassa water level rise is the historical recorded flood that had occurred in 1998/99 (WRDB, 2007; WWDSE, 2001). In monetary terms, this destruction accounted for about €5.4 million (WRDB, 2007). The corresponding impact on human well-being and environment are not yet studied as to the author´s knowledge. However, it is apparent that when the environmental factors change, for whatever reason, the individuals, communities and even economic sectors that depend on these factors are also affected in myriad ways (UNEP, 2008).

8.4.6. "Responses" (R)

Various policies are available in Ethiopia which can serve as legal ground towards sustainable management of water resources in general and Lake Hawassa in particular. A "response" by society or policy makers is the result of an undesired impact and can affect any part of the chain between driving forces and impacts (Kristensen, 2004). Pursuing the enforcement of current policy instruments is taken as an option in this study and the following paragraphs discuss the existing policies, proclamations and programmes.

While grouping the main findings of the first four components of the DPSIR framework as shown in the previous sections, the six major environmental issues as shown in *figure 8.8* are apparently identified to examine the existing "response" instruments. These issues are: deforestation, population growth and density, the use of wood as fuel, land tenure system, unsustainable utilization of land resources, and socio-political changes. Corresponding to the six key issues which belong to the D-P-S-I elements, there found about ten relevant and overlapping response instruments (*more number of responses can be identified if more time was available than this study*) that are directed towards managing them.

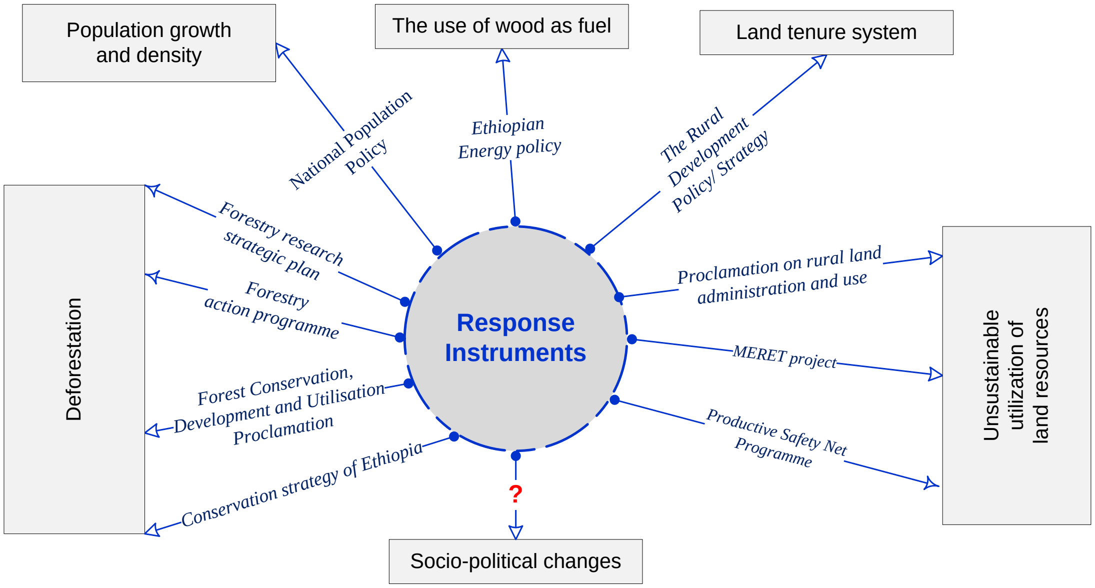


Figure 8.8. List of responses (the red question mark at the bottom of the circle shows the gap of response instrument)

As shown in the above figure, a couple of response instruments have been designed by the government to mitigate the deforestation problem (*the left most box*). These include: Forestry Research Strategic Plan, Forestry Action Programmes, Forest Conservation, Development, and Utilization Proclamation, and Conservation Strategy of Ethiopia. These response instruments provide legal framework for sustainable management of forest resources.

Regarding population growth, the National Population Policy (NPP) articulated the Government's position on the relationship between demographic and economic growth, with sustainable and equitable human development as its central theme. The policy stated that without a reduction in population growth, the efforts to reduce poverty and the achievement of national development goals would be jeopardized.

The Ethiopian Energy Policy encourages energy mix, and in the long-term, a replacement of the traditional sources of fuel by modern technologies. Parallel to this, the policy promotes country-wide afforestation programme to supplement traditional fuels.

The rural development policy and strategy justifies the voluntary resettlement programmes (can also be viewed as a response against population density). This response pays attention to the land tenure issue and the proper use of land. Important changes such as the moratorium on land re-distribution and the distribution of land certificates are given a legal basis in this instrument.

The proclamation on rural land administration and use defines the individual land use and disposal rights. It defines obligations of rural land users and land use restrictions. Thus, protection of land becomes an obligation and failure to protect can lead to loss of title.

The last, but not the least, is the issue of socio-political changes that induce uncertainty and insecurity during transition periods of political regimes. Dessie and Christiansson (2008) identified that large areas of forest were cut down during periods of political transition as a result of the political vacuum. Instruments to avoid such problems were not recognized by the stakeholders (the red question mark at the bottom of *figure 8.8*) except that they recommend creation of ownership feeling among the community so that socio-political changes have less effect on the natural resources. Such occurrences are exemplified in some parts of Ethiopia.

Generally, as recognized from the causal chains, there is a loose link between response instruments (R) and the rest of the DPSIR components which are probably attributed to the inefficiency of institutional arrangements in implementing an established regulation. Such situation reminds the policy makers to pay more attention to the appropriate implementation of available management instruments together with designing new ones. Long-term education for the implementing bodies and for the general community seems to work at this point.

8.5. Summary and conclusions

The overall result of this section shows that the lake level rise (State) of Lake Hawassa has been accompanied by some anthropogenic factors. The immediate causes (Pressures) of this level rise comprise sedimentation into the lake and increased runoff in which both pressures are perceived to be influenced by land use changes, deforestation and unsustainable use of land resources (Drivers). These drivers in turn impacted by indirect drivers (indirect Drivers) that comprise population growth and density, expansion of agriculture, the use of wood as fuel, socio-economic changes, and the existing land tenure system. The impact of lake level rise was assessed in view of its risk to produce flood (Impact) which usually impacts the environment and human well-being in addition to economic losses.

This conceptual exercise about the causal paths is found to provide an aid to logically combine information from different sources to tell an integrated story. It effectively highlights the causal relationships and provides a useful first step towards the establishment of a full-fledged causal network for the major environmental problems of Lake Hawassa hydro-system. The results provide a better understanding of why and how people destroy their environment and careful translation of this understanding into plans and actions enables the stakeholders to prevent or reduce further destruction. The solutions are at the reach of stakeholders by acting locally while thinking at watershed scale.

The structuring and integration of available and new environmental information using DPSIR conceptual framework is found to illustrate the overall status of the Lake Hawassa hydrosystem and paved a better understanding towards sustainable management of the ecosystem as a whole.

With regard to the last component of the framework: R, a set of existing policies and legal documents were assessed to explore the possible management options towards the other four components of the model. It was then recognized that the available policies and legal documents have a promising potential for mitigation, adaptation or curative actions against the anthropogenic wings of the problems at hand.

8.6. Limitation of the study

Many of the relationships between the human system and environmental system are complex and may not be well understood (Maxim et al., 2009). The underlying assumption of simple causal relations cannot fully capture the complexity of interdependencies in the real world (Spangenberg et al., 2002). Besides, it is sometimes difficult to provide conclusive evidence of a cause-effect relationship as is required for the application of the DPSIR logic (EEA, 2005).

Generally, a full-fledged causal-link is not always necessary or, if any, it needs long and intensive researches of integrated approach. In this study, the overall causal links were derived from available information, researcher’s and stakeholders’ experience on the topic at hand. In this regard, it is strongly recommended to have future researches of similar framework, but with filling gaps in that this study falls short of, if possible, by generating primary evidences.

Chapter 9. Synthesis

9.1. General remarks

The main objective of this study was to investigate the causes of Lake Hawassa water level variability in general and its resultant rise in particular. A number of researchers attempted to address the issue and this research can be viewed as one of those efforts. In this study, the impact of climate variability and sedimentation was in a greater detail than has been done before.

Particularity of this research is depicted by the diverse approaches employed to provide a comprehensive insight into the hydrological status of Lake Hawassa. The logical combination of coherence analysis, regime shift detection, trend analysis, lake level simulation, bathymetry surveys, sediment yield modeling, and DPSIR analysis enables the thesis to provide an integrated story about the characteristics of the hydrosystem. It can be considered as one of the potential documents to guide the future management of Lake Hawassa. The following section tries to summarize the over-all findings of this study in the form of DPSIR components.

9.2. Synthesis of causal links

The temporal variability of Lake Hawassa water level is shown to be influenced by the combined effect of anthropogenic, natural and climate related factors. *Figure 9.1* (below) synthesized a simplified relationship among these factors in the DPSIR framework.

As depicted by *figure 9.1*, the causes of Lake Hawassa water level rise can be broadly classified into two: hydro-climatic variability (a) and anthropogenics (b).The occurrences of climate shifts and extreme events such as ENSO phenomena are among some of the variabilities responsible for the resultant rise of the lake level. The neotectonic process is believed to affect the lake level but not investigated in this study. Sedimentation in the lake and the increasing trend of runoff from the watershed are among the immediate causes to affect the lake level variability and these pressures can be related to both natural and human inductions and the dominant factors are not yet fully analyzed. Further in the causal chain, the sedimentation and increased runoff are manifested by land use changes, deforestation and unsustainable use of land.

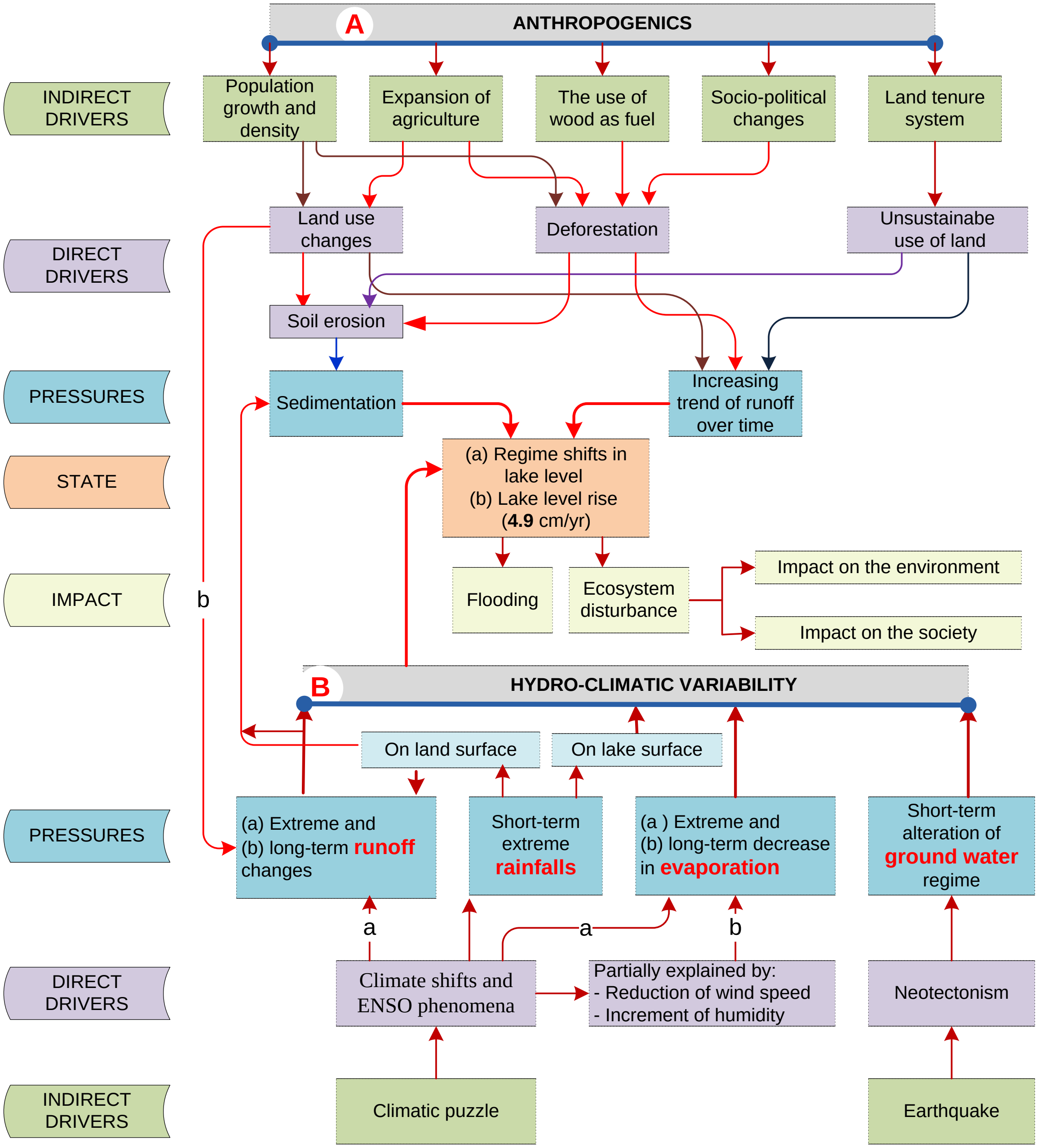


Figure 9.1. Summary of causal link and relationship among anthropogenic and natural factors

9.3. Overall Conclusions

The primary factor that influences the level rise of Lake Hawassa is found to be climate variability. This factor is manifested by the extreme and simultaneous occurrences of high rainfall and the corresponding runoff which are responsible for the entry of extreme amount of water into the lake system.

The two prominent climate events which strongly influence the hydrology of Lake Hawassa are: the climate shift of North Pacific Ocean that occurred in 1976/77 and the El Niño events that occurred in 1972-73, 1982-83, 1997-98, and 2009-10. The neotectonic activities that occurred in 1996, ´97 and ´98 consecutively, are also considered to involve in the interplay but direct evidences are not available.

In the long-term perspective, "rainfall" has neither been significantly increasing nor decreasing over time on both annual and monthly bases. Despite this, "runoff" has shown significant increasing trend. The interplay between these different trends is considered to justify the role of land use/cover changes at least in modifying the impact of climate.

The increased runoff has been perceived to be directly driven by land use changes, deforestation, and unsustainable use of land. These direct drivers (D) have also been perceived to result from population growth and density, agricultural development, the use of wood as fuel, socio-economic changes, and the prevailing land tenure system and indirect drivers (iD). The effect of sedimentation in reducing the storage capacity of the lake is found to be low (0.08% per year) as compared to the total volume of water in the lake.

The historical maximum recorded flood which had occurred in 1998/99 appeared to be caused by the simultaneous occurrence of the 1996 high rainfall followed by the worst El Niño (1997-98) by which runoff, rainfall, and evaporation were affected. The tectonic activities that occurred in the consecutive years of 1996, ´97 and ´98 were also assumed to affect the ground water flow, but no concrete evidence to verify it.

It is generally concluded that the lake level variability of Lake Hawassa is more reactive to extreme climate events than the long-term natural and anthropogenic factors.

9.4. Perspectives

This study provides a new dimension of articulating the causes of Lake Hawassa water level rise by considering both anthropogenic and natural factors on one hand and long-term and extreme temporal extents on the other. It was shown that almost the entire water balance components have been interplayed in one way or another in affecting the temporal variability of the lake level in general and its resultant increasing trend in particular.

The association of flood from Lake Hawassa to the climate anomalies resulting from natural mechanisms could have two managerial implications; on one hand, it would be difficult to mitigate the problem because of its dependence on macro-scale processes and on the other hand, an optimistic view of those large El Niño events which are notorious for their extreme floods are acceptably predictable within period at lead times of up to two years (Chen et al., 2004). Such opportunities are useful to get an alarm against the urgency of flood occurrences, even in the absence of local monitoring data and downscaling can be endorsed and mainstreamed in a regular early warning and assessment activities to reduce the impact of potential flood risks.

This causal-loop is by no means exhaustive, but believed to provide an orderly guidance for future research and development interventions. As noted by Gregersen et al. (2007), integrated watershed management can only be effective if they are grounded in the technical realities of what is going on with the soil, water and biophysical resources and the interactions between them. Thus fundamentally, an effective interaction or combination of institutional and technical information is required for successful watershed management that results in lasting benefits for the stakeholders living in the watershed.

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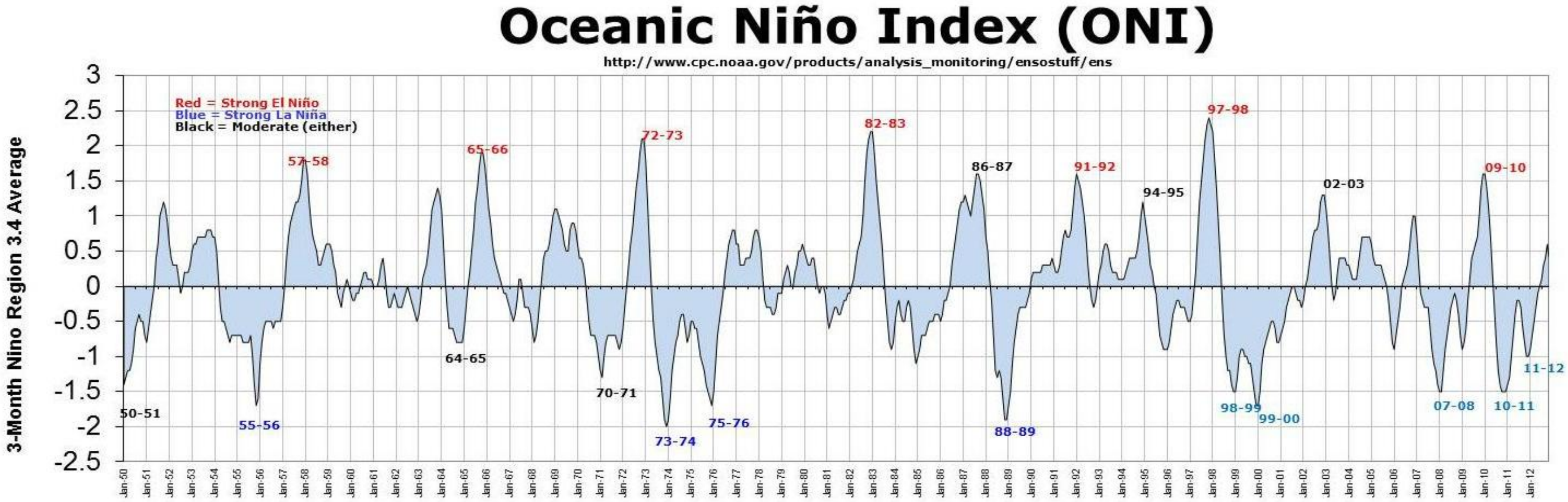
Appendices

Appendix 1: (A) Oceanic Nino Index (ONI) Source: Null (2012) (accessed in September 2012)



(B) El Niño and La Niña Years and Intensities: Based on Oceanic Niño Index (ONI)

El Niño			**La Niña**		
Weak	**Moderate**	**Strong**	**Weak**	**Moderate**	**Strong**
1969	1968	1972	1971	1970	1973
1976	1986	1982	1974	1998	1975
1977	1987	1991	1983	2007	1988
2004	1994	1997	1984		1999
2006	2002		1995		2010
	2009		2000		
			2005		
			2011		

Appendix 2: RSI result of annual average lake level

	Av. Lake Depth (m)	RSI	Mean	Weighed	Length	P	Outliers
1970	19.64	0.00	19.70	19.68	8		
1971	19.83	0.00	19.70	19.68	8		
1972	20.26	0.00	19.70	19.68	8		0.76
1973	19.92	0.00	19.70	19.68	8		
1974	19.53	0.00	19.70	19.68	8		
1975	19.37	0.00	19.70	19.68	8		
1976	19.36	0.00	19.70	19.68	8		
1977	19.67	0.00	19.70	19.68	8		
1978	20.40	0.63	20.12	20.10	9	0.02	
1979	20.74	0.00	20.12	20.10	9		0.68
1980	20.33	0.00	20.12	20.10	9		
1981	19.86	0.00	20.12	20.10	9		
1982	19.72	0.00	20.12	20.10	9		
1983	20.15	0.00	20.12	20.10	9		
1984	20.22	0.00	20.12	20.10	9		
1985	19.77	0.00	20.12	20.10	9		
1986	19.90	0.00	20.12	20.10	9		
1987	20.27	0.88	20.43	20.43	6	0.06	
1988	20.32	0.00	20.43	20.43	6		
1989	20.71	0.00	20.43	20.43	6		
1990	20.78	0.00	20.43	20.43	6		
1991	20.33	0.00	20.43	20.43	6		
1992	20.17	0.00	20.43	20.43	6		
1993	20.72	1.10	21.20	21.16	10	0.001	
1994	20.70	0.00	21.20	21.16	10		0.95
1995	20.53	0.00	21.20	21.16	10		0.69
1996	20.92	0.00	21.20	21.16	10		
1997	21.33	0.00	21.20	21.16	10		
1998	21.98	0.00	21.20	21.16	10		0.53
1999	21.90	0.00	21.20	21.16	10		0.59
2000	21.25	0.00	21.20	21.16	10		
2001	21.31	0.00	21.20	21.16	10		
2002	21.37	0.00	21.20	21.16	10		
2003	20.87	-0.29	21.00	20.99	8	0.34	
2004	20.58	0.00	21.00	20.99	8		
2005	20.56	0.00	21.00	20.99	8		
2006	20.72	0.00	21.00	20.99	8		
2007	21.46	0.00	21.00	20.99	8		0.93
2008	21.47	0.00	21.00	20.99	8		0.92
2009	21.19	0.00	21.00	20.99	8		
2010	21.16	0.00	21.00	20.99	8		

RSI: Regime Shift Index

Mean: Equal-weighed arithmetic means of the regimes

Weighed: Weighed means of the regimes using the Huber's weight function with the parameter = 1

Length: Length of the regimes

P: Significance level of the difference between the mean values of the neighboring regimes based on the Student's two-tailed t-test with unequal variance (TTEST procedure in Excel)

Appendix 3: RSI result of annualtotal rainfall at Hawassa station

	Annual rainfall at Hawassa Met Station (mm)	RSI	Mean	Weighed	Length	P	Outliers
1973	726	0	830	830	3		
1974	937	0	830	830	3		
1975	826	0	830	830	3		
1976	954	0.18	954	954	1		
1977	1226**	0.15	1130	1130	2		
1978	1033	0	1130	1130	2		
1979	968	-0.21	881	881	2		
1980	794	0	881	881	2		
1981	1040	0.047	1064	1064	3		
1982	992	0	1064	1064	3		
1983	1160	0	1064	1064	3		
1984	725	-0.29	813	813	2		
1985	902	0	813	813	2		
1986	1194	0.13	948	942	9		0.55
1987	955	0	948	942	9		
1988	957	0	948	942	9		
1989	1025	0	948	942	9		
1990	751	0	948	942	9		0.73
1991	889	0	948	942	9		
1992	975	0	948	942	9		
1993	928	0	948	942	9		
1994	861	0	948	942	9		
1995	1004	0.03	1099	1099	4		
1996	1189	0	1099	1099	4		
1997	1055	0	1099	1099	4		
1998	1146	0	1099	1099	4		
1999	810	-0.12	882	882	6		
2000	822	0	882	882	6		
2001	1022	0	882	882	6		1.00
2002	920	0	882	882	6		
2003	821	0	882	882	6		
2004	896	0	882	882	6		
2005	998	0.43	1002	1025	6		
2006	1198	0	1002	1025	6		0.81
2007	1157	0	1002	1025	6		
2008	915	0	1002	1025	6		
2009	704	0	1002	1025	6		0.44
2010	1039	0	1002	1025	6		

**Highest annual rainfall in the period

Appendix 4: RSI result of Mean annual Stream flow at Tikur Wuha (m^3/s)

	Mean annual Stream flow (m^3/s)	RSI	Mean	Weighed	Length	P	Outliers
1980	0.76	0	1.89	1.95	7		0.38
1981	2.09	0	1.89	1.95	7		
1982	2.14	0	1.89	1.95	7		
1983	2.69	0	1.89	1.95	7		0.61
1984	1.88	0	1.89	1.95	7		
1985	1.71	0	1.89	1.95	7		
1986	1.945	0	1.89	1.95	7		
1987	2.18	1.12	2.39	2.39	3	0.08	
1988	2.48	0	2.39	2.39	3		
1989	2.5	0	2.39	2.39	3		
1990	2.9	0.51	2.90	2.90	1		
1991	2.6	-0.08	2.65	2.65	4		
1992	2.55	0	2.65	2.65	4		
1993	2.85	0	2.65	2.65	4		
1994	2.6	0	2.65	2.65	4		
1995	2.92	0.74	3.12	3.11	3		
1996	3.6	0	3.12	3.11	3		0.91
1997	2.84	0	3.12	3.11	3		
1998	3.86	0.04	3.39	3.39	9		0.96
1999	4.02	0	3.39	3.39	9		0.72
2000	2.66	0	3.39	3.39	9		0.61
2001	3.12	0	3.39	3.39	9		
2002	3.42	0	3.39	3.39	9		
2003	3.535	0	3.39	3.39	9		
2004	3.65	0	3.39	3.39	9		
2005	3.2	0	3.39	3.39	9		
2006	3	0	3.39	3.39	9		

Appendix 5: RSI result of annual runoff coefficient

	Runoff coefficient of Tikur Wuha sub-watershed (C)	RSI	Mean	Weighed	Length	P	Outliers
1981	0.1	0	0.11	0.11	7		
1982	0.1	0	0.11	0.11	7		
1983	0.14	0	0.11	0.11	7		0.84
1984	0.1	0	0.11	0.11	7		
1985	0.09	0	0.11	0.11	7		
1986	0.12	0	0.11	0.11	7		
1987	0.1	0	0.11	0.11	7		
1988	0.13	0.85	0.13	0.13	2	0.01	
1989	0.13	0	0.13	0.13	2		
1990	0.17	0.31	0.17	0.17	2	0.09	
1991	0.16	0	0.17	0.17	2		
1992	0.12	-0.16	0.14	0.14	6	0.03	
1993	0.14	0	0.14	0.14	6		
1994	0.14	0	0.14	0.14	6		
1995	0.15	0	0.14	0.14	6		
1996	0.15	0	0.14	0.14	6		
1997	0.13	0	0.14	0.14	6		
1998	0.17	0.88	0.18	0.18	8	0.01	
1999	0.24	0	0.18	0.18	8		0.48
2000	0.14	0	0.18	0.18	8		0.70
2001	0.15	0	0.18	0.18	8		0.93
2002	0.2	0	0.18	0.18	8		
2003	0.2	0	0.18	0.18	8		
2004	0.2	0	0.18	0.18	8		
2005	0.16	0	0.18	0.18	8		

Appendix 6: RSI result of annual total lake evaporation as computed from pan-evaporation (mm)

	evaporation	RSI	Mean	Weighed	Length	P	Outliers
1986	1720	0	1717	1717	2		
1987	1713	0	1717	1717	2		
1988	1647	-0.29	1659	1659	8	0.08	
1989	1554	0	1659	1659	8		
1990	1625	0	1659	1659	8		
1991	1606	0	1659	1659	8		
1992	1682	0	1659	1659	8		
1993	1696	0	1659	1659	8		
1994	1818	0	1659	1659	8		0.97
1995	1645	0	1659	1659	8		
1996	1298	-1.83	1329	1329	5	0.00001	
1997	1343	0	1329	1329	5		
1998	1236	0	1329	1329	5		
1999	1385	0	1329	1329	5		
2000	1382	0	1329	1329	5		
2001	1258	-0.18	1295	1295	7	0.36	
2002	1318	0	1295	1295	7		
2003	1376	0	1295	1295	7		
2004	1301	0	1295	1295	7		
2005	1331	0	1295	1295	7		
2006	1192	0	1295	1295	7		
2007	1285	0	1295	1295	7		