Ministry of Water & Energy (MoWE)
The Federal Democratic Republic of Ethiopia

THE STUDY ON GROUNDWATER RESOURCES ASSESSMENT IN THE RIFT VALLEY LAKES BASIN IN THE FEDERAL DEMOCRATIC REPUBLIC OF ETHIOPIA

FINAL REPORT

SUPPORTING REPORT

March 2012

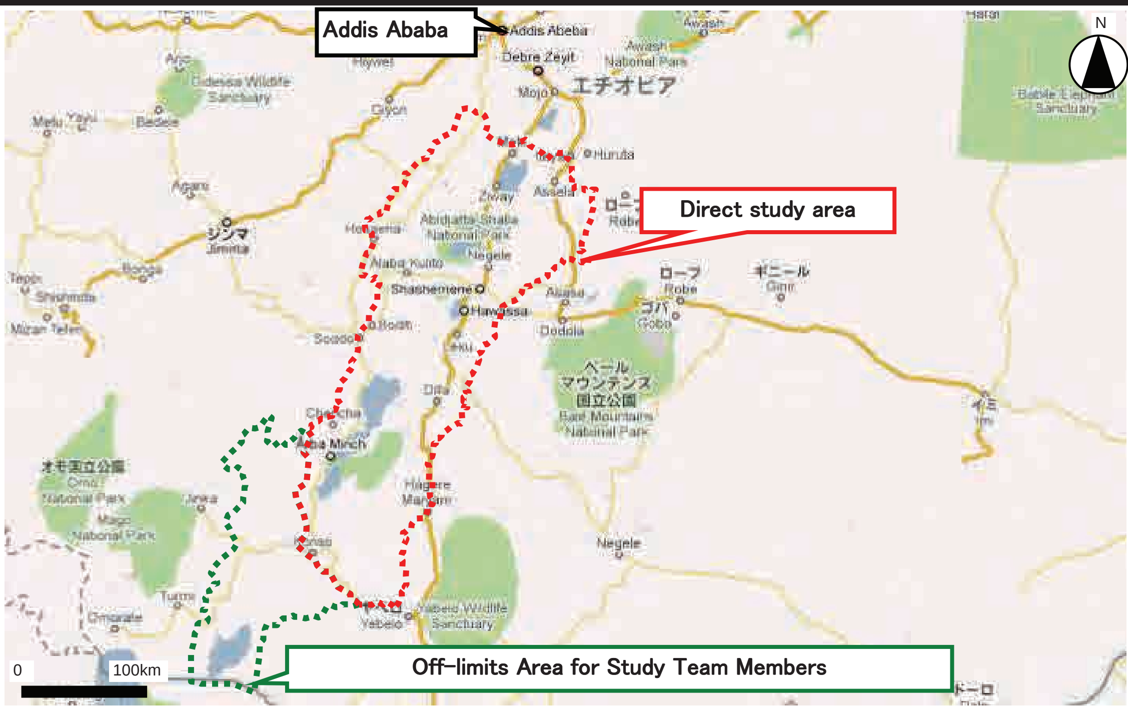
Japan International Cooperation Agency (JICA)

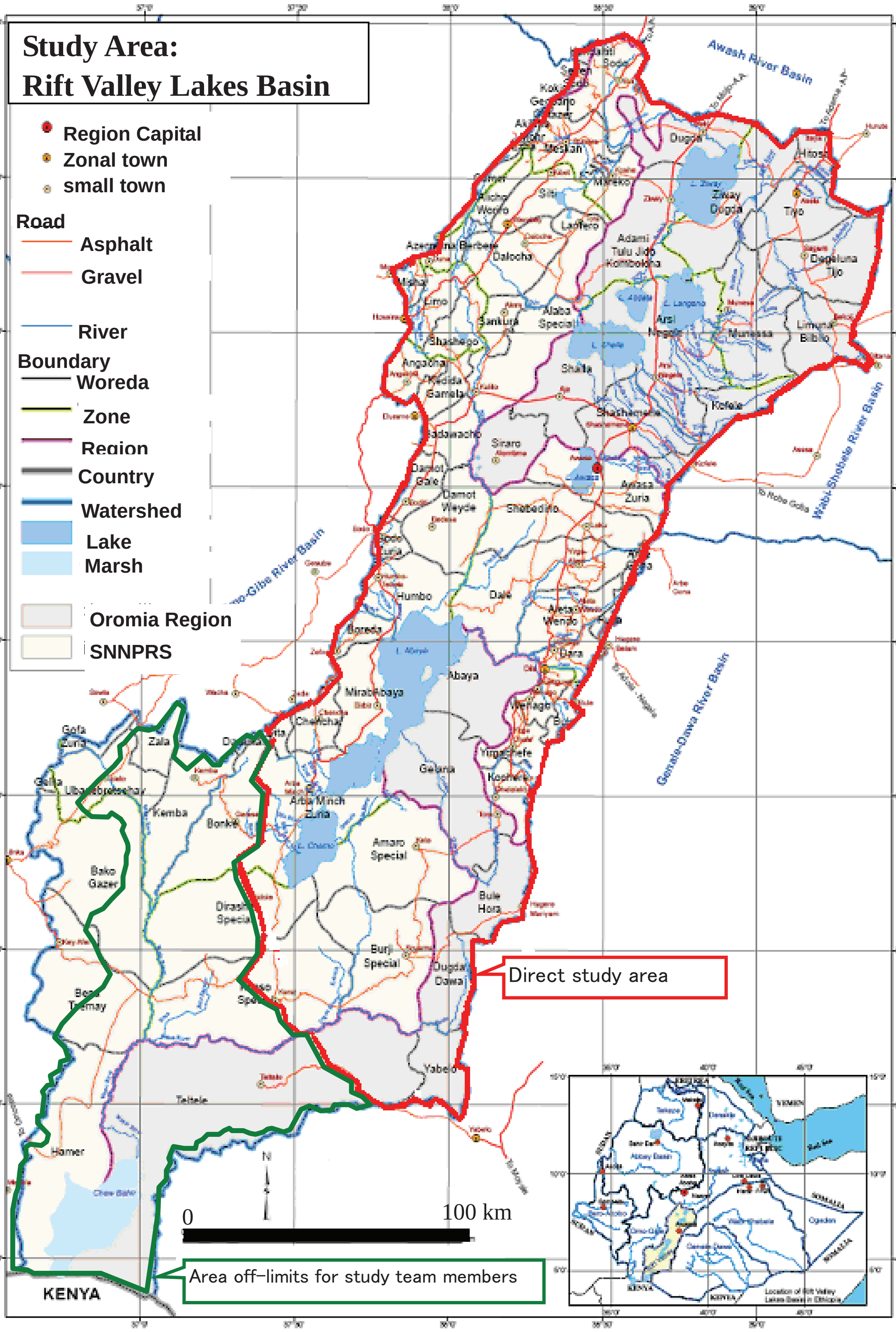
Kokusai Kogyo Co., Ltd.

In this report, the project cost is estimated using the November 2011 price and at an exchange rate of 1 US$=75.84 Japanese Yen, ETB (Ethiopia Birr)1= 4.451 Japanese Yen

Location of Ethiopia

Location of Study Area




Study Area:
Rift Valley Lakes Basin
Region Capital
Zonal town
small town
Road
Asphalt
Gravel
River
Boundary
Woreda
Zone
Region
Country
Watershed
Lake
Marsh
Oromia Region
SNNPRS
Awash River Basin
Wabi Shebele River Basin
Genale-Dawa River Basin
Direct study area
Area off-limits for study team members
0
100 km
N
KENYA

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Minutes of Meeting

M/M- 0 Minutes of Meeting on Inception Report
M/M- 1 Minutes of Meeting on First Steering Committee Meeting
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M/M- 3 Minutes of Meeting on Third Steering Committee Meeting
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LIST OF ABBREVIATIONS

AAWSA	Addis Ababa Water Supply and Sewerage Authority
AAU	Addis Ababa University
AFD	Agence Française de Dévelopement
BoFED	Bureau of Finance and Economic Development
CIDA	Canadian International Development Agency
CPI	Consumer Price Index
CRS	Catholic Relief Services
CSA	Central Statistical Agency
DfID	Department for International Development
DTH	Down the Hole Hammer
EAP	Economically Active Population
EIA	Environmental Impact Assessment
EIGS	Ethiopian Institute of Geological Survey
ENGDA	Ethiopian National Groundwater Database
ENGWIS	Ethiopian National Groundwater Information System
EPE	Environmental Policy of Ethiopia
EPSA	Ethiopian Postal Service Agency
EROAM	Economic Resources Optimization and Allocation Model
ETC	Ethiopian Telecommunications Corporation
EU	European Union
EWTEC	Ethiopian Water Technology Center
FINDA	Finnish Development Agency
GDP	Gross Domestic Product
GEF	Global Environmental facility
GIS	Geographic Information System
GNI	Gross National Income
GPS	Global Positioning System
GRP	Gross Regional Product
GSE	Geological Survey of Ethiopia
GTZ	German Technical Cooperation
HES	Horizontal Electric Sounding
HICE	Household Income, Consumption and Expenditure
IEE	Initial Environmental Examination (Evaluation)
IDC	
JICA	Japan International Cooperation Agency
KfW	Kreditanstalt für Wiederaufbau
MER	Main Ethiopian Rift
MoE	Ministry of Mines
MoH	Ministry of Health
MoWE	Ministry of Water & Energy
MP	Master Plan
NGOs	Non-Government Organizations
NMSA	National Meteorological Services Agency
NWP	National Water policy
PA	Preliminary Environmental Assessment
PASDEP	Plan for Accelerated and Sustained Development and Poverty
RHBs	Regional Health Bureaus
ROE	Rest of Economy

RVLB	Rift Valley Lakes Basin
RVS	Rift Valley Study
RWBs	Regional Water Bureaus
RWS	Rural Water Supply
SNNPRS	Southern Nations, Nationalities and Peoples' Regional State
TVETC	Technical and Vocational Education and Training College
UAP	Universal Access Program
UNDP	United Nations Development Programme
UNICEF	United Nations International Children Fund
UTM	Universal Transversal Mercator
VES	Vertical Electric Sounding
WASHCO	Water Supply and Health Committee
WFB	Wonji Fault Belt
WHD	Woreda Health Desks
WLR	Water level Recorder
WMO	World Meteorological Organization
WRDF	Water Resources Development Fund
WSDP	Water Supply Administration Agency
WWMEO	Woreda Water, Mining and Energy Office

Chapter 1

Meteorology and Hydrology

1 Meteorology and Hydrology

1.1 Status of hydrometeorological stations and data

1.1.1 Meteorological stations and data

All hydrological and meteorological stations are operating under the Ministry of Water Resources. Meteorological data is available for the period from early 1950's for some stations but the range varies from station to station. Hydrological data is available for the period from mid 1960's at a one station but majority are from the 70's onward.

1) Meteorological data

Meteorological data is dealt with by National Meteorological Service Agency (NMSA) which has its headquarter in Addis Ababa. NMSA has branch offices in each region across the country and there are hundreds of observation stations under each branch office. Ethiopia is a member of World Meteorological Organization (WMO) and the measurements and data collection are conducted according to WMO guidelines. Observation stations are classified as follows according to the WMO standard:

Class 1: 12 parameters are recorded. The data are transmitted to branch offices daily by radio. It is also a called synoptic station if air pressure is measured.

Class 2: Non existent in Ethiopia

Class 3: Minimum and maximum temperature and rainfall amount are measured

Class 4: Only rainfall amount is measured

There are a total of 81 meteorological stations within the Study Area (inside and on the border of rift valley lakes basin) and all the stations operate under NMSA Awassa branch office although some of the stations are located in Oromiya region. This is because those stations located on the south of Ziway in Oromiya region were handed over to Awassa branch for administrative convenience a few years ago. Branch offices collect measured data daily from Class 1 stations and every month from the other stations and send the data to the head office after quality check (ex. discard unreliable data) every month.

Figure 1.1: Class 1 Station in Ziway

Review of some of the raw data collected during the field work and interview with the persons in charge at some branch offices and in class 1 stations revealed that not all the stations properly or regularly measure all the items of measurement due to breakdown of instruments and for other reasons. Therefore the amount of data available for analysis is much smaller than that was expected from the number of stations and observation period.

The number of stations under each category within the Study Area is shown in the table below.

Table 1.1: Number of Stations under Each Category

Synoptic	Class 1 (Primary)	Class 2	Class 3 Class 4
2	7	None	72

a. Rainfall

Rainfall is recorded as a daily total value at every station using the standard rain gauge. The

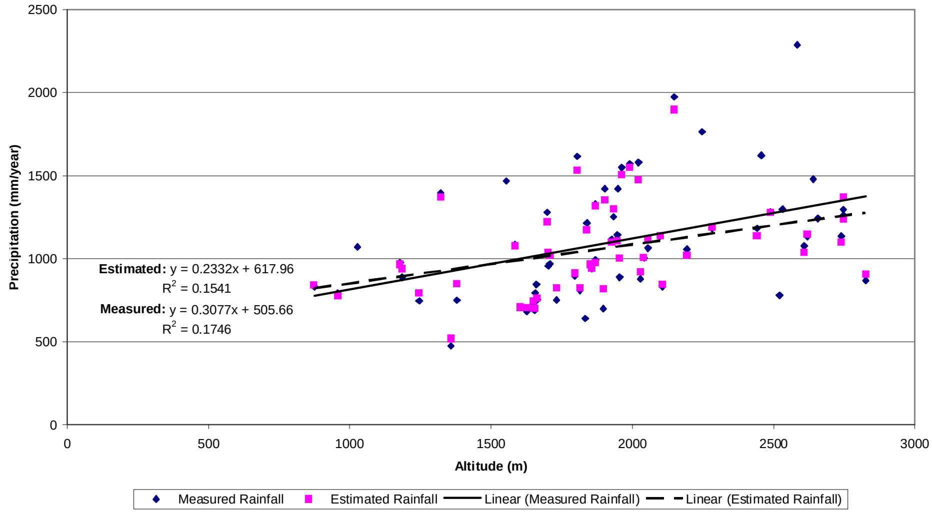


Figure 1.2: Rainfall – Altitude Relation

(Source: Halcrow 2008)

annual rainfall pattern and amount of precipitation is variable from area to area within the Study Area. However, it is known that the amount of precipitation is moderately related with altitude. Thus, in general, more precipitation occurs at the mountainous edge of Study Area (rift valley lakes basin) than in the flat plain area along the central axis of the Study Area. An example of this precipitation-altitude relation at major stations is shown in Figure 1.2.

On the other hand, the monthly rainfall distribution pattern changes systematically toward the south from Ziway to Konso area. In Ziway area, the rainy season when much of the annual precipitation falls is in August and September; however in Awassa, some 100km to the south in the rift valley, precipitation is more evenly distributed over a longer period of April to September. In Arba Minch area, about 150km further south from Awassa, the precipitation distribution shows a by-modal pattern, and this pattern becomes conspicuous in Konso, which is located a 100km further south. Figure 1.38 illustrates this pattern of change in rainfall distribution pattern along the NS axis of the Rift Valley Lakes Basin.

b. Temperature

Temperature is recorded as daily maximum and minimum values at class 3 stations above. As observed in the rainfall amount, temperature is also closely related to the altitude and the relation is clearer. An example of this temperature-altitude relation at major stations is shown in Figure 1.3.

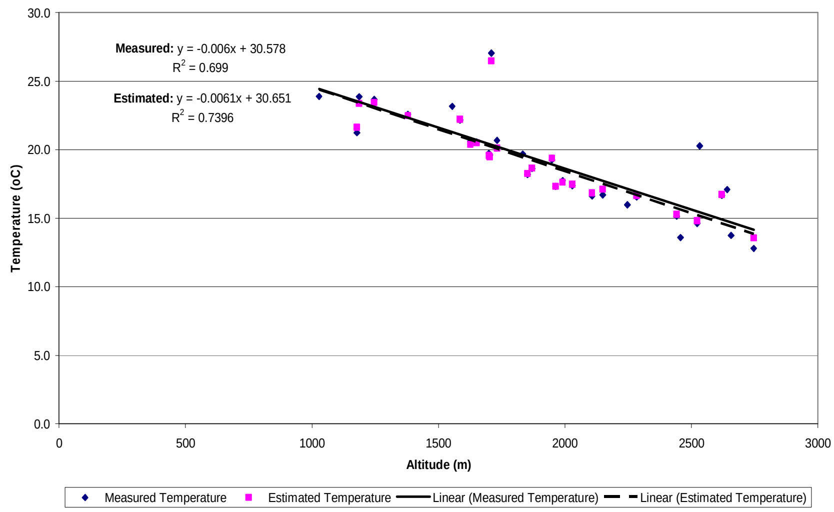


Figure 1.3: Temperature – Altitude Relation

(Source: Halcrow 2008)

Figure 1.38 shows the monthly temperature distribution pattern, for the major cities of Ziway, Awassa, Arba Minch, and Konso. The annual range in temperature change is within 5^{o}C. The months of February and March are the hottest months in every town, while September to December is also another warm period in the southern towns of Arba Minch and Konso.

c. Evapotranspiration

Evapotranspiration is not usually measured directly, but in most cases estimated by some methods based on other measured parameters. In order to calculate evapotranspiration, at least the data of daily temperature is necessary. This data is available at Class 1, and 3 stations. For more complex methods of calculation such as the Penman method, the data from only class one stations can be used.

Evaporation is measured at class 1 stations by both a class a pan and a Piche evaporimeter. The data, however, is generally incomplete and needs interpretation before analysis. Halcrow

2008 estimated the reference crop potential evapotranspiration for 12 stations using the Penman-Monteith formula. The calculation was based only on long-term average monthly

Table 1.2: Monthly Evapotranspiration for 12 Stations

(Source: Halcrow 2008)

Station	Month												Total
	1	2	3	4	5	6	7	8	9	10	11	12	
ARKOFE21	113	110	114	102	104	85	79	81	83	100	107	104	1182
ARKULU11	135	130	144	135	140	114	105	102	100	136	140	136	1517
ARSAGU21	110	101	119	104	104	83	81	82	89	102	103	107	1185
GGJINK11	121	119	132	111	105	90	96	100	107	111	108	112	1311
GGKONS11	152	158	171	138	131	119	110	133	144	138	137	141	1671
GGMIRA21	140	138	158	144	141	133	122	128	139	135	129	134	1642
SHHOSA11	117	117	133	118	116	94	84	87	98	118	117	121	1320
SHZIWA11	128	127	144	139	148	138	118	120	119	135	131	128	1578
SIAMAR11	150	148	159	124	111	95	93	108	127	119	128	143	1504
SIDILL11	113	114	128	113	110	94	86	99	97	103	107	109	1272
SIWOLA11	149	147	152	130	117	98	88	98	108	126	149	152	1514
SIYABE31	150	148	159	124	111	95	93	108	127	119	128	143	1504

parameters due to data quality limitations. The result is quoted below.

d. Other hydrometeorological data

There are at least 12 items that are measured at Synoptic and Class 1 stations. Some other parameters are also measured and those are used mainly for agronomy such as soil moisture content. The list of 12 parameters measured at Synoptic stations is presented below.

Table 1.3: Measured Parameters at Synoptic Stations

	Parameter	Method
1	Daily rainfall	Rain fall gauge (manual, automatic)
2	Daily temperature (Max and Min)	Max and min thermometer (mercury)
3	Relative humidity	Hygrometer
4	Dew point temperature	Calculated
5	Evaporation	Class A pan, Piche evaporimeter
6	Sunshine duration	Campbell-stokes recorder
7	Wind speed/direction	Cup anemometer, Wind mill anemometer
8	Cold cloud duration	Satellite image interpretation, meteo-baloon
9	Air pressure	Air pressure gauge
10	Weather forecast	Computation and assessment
11	Visibility	Visual observation
12	Soil temperature	Mercury thermometer

1.1.2 Hydrological observation stations and data

The hydrological observation stations are classified into two types: river gauging stations and lake level gauging stations. There are a total of 46 hydrological observation stations and nine lake level gauging stations in the Study Area.. Those located on the north of Lake Awassa operate under Addis Ababa branch office and those on the south including the ones on Lake Awassa operate under Awassa branch office of hydrology department. Most of the stations are simple staff-gauged measurement points where benchmarks were established on a stable rock surface etc. Only at some locations of major rivers, a weather resistant structure is built on the river bank to house an automatic level recorder (see to Figure 1.4).

Figure 1.4: Gauging Station on Bilate River

At every gauging station, river stage is measured twice a day and the data is regularly gathered by the branch offices in charge. The office sends the data to the head office in paper form and it is then, inputted to a computer and digitally formatted. Actual flow measurements are also conducted as often as once a month (usually once every few months) at major river gauging stations using a flow velocity meter. Cross sectional survey of the stream is also conducted at the same time and the discharge is calculated.

Interview with officers in charge of relevant offices and site visits to some gauging stations revealed that these established staff gauges are constantly subject to tampering by local children and damage by seasonal food events. This makes regular and accurate measurements nearly impossible. In addition, creating a stage-discharge rating curves at a station takes a number of measurements. Meanwhile the river beds and banks have changed their shapes over the time. Therefore it is very difficult to reasonably compute rive discharge only from stage data.

a. River flow

The analysis of available river discharge data by Halcrow 2008 revealed that the stage-discharge rating curves are changing over time at most stations. This makes it difficult to directly calculate the discharge of the rivers using the curves established even a few years ago.

The monthly discharge measurement data obtained from the Hydrology Department of Ministry of Water Resources has been compiled to show the range of discharges for major rivers in the Study Area. The period of data extends from 1970 to 2006. Recent data was not available.

Table 1.4: Discharge of Major Rivers

River	Station No	Sub-basin*	Catchment Area (km^2)	Discharge (m^2/s)	
				Max	Min
Katar	081019	Eastern Ziway	3350	176.3	0.00
Meki	081018	Western Ziway-Abiyata	2433	218.4	0.00
Djidu	081006	Lake Shalla	7310	132.1	0.00
Bilate	082008	Bilate	1980	104.6	0.04
Gidabo	082016	Gidabo	646	76.7	0.00
Gelana	082035	Gelana	NA	48.3	0.00
Segen	083001**	Segen	4850	44.8	0.00
Weyto	083002	Bezo-Weyto	4569	139.5	0.00

* sub-basin classification is after Halcrow 2008, Only 3 year data available

The figures suggests that the rivers in the southern part of the Study Area tend to have smaller specific discharges and most rivers run dry at least for some period of a year

b. Lake level

The lake levels are observed at the nine sites in the following table. These stations cover all the major lakes in the Study Area except for lake Chew Bahir located at the southern most end of the Study Area. The observation started in the late 60's or in early 70's. Typical observation point setup is the several vertically-erected staff scales that are lined up perpendicular to the shoreline. The staff scales are positioned with an interval of several to 10 meters depending on the topography. The photo shows the gauging point at Lake Awassa. One of the erected staff scales has been destroyed, with only the steel base remaining. The list of stations is presented below.

Figure 1.5: Gauging Point at Lake Awassa

Table 1.5: Lake Level Gauging Stations

Lake name	Site	Lat	Long	Altitude
Ziway	ZIWAY	7.90	38.75	1641.94
Abiyata	near. Arore	7.55	38.70	1592.36
Langano	near a Hotel	7.53	38.52	1584.33
Shala	Gale	7.30	38.37	NA
Abaya	near Arba Minch (Lante)	6.02	37.60	1178.75
Abaya	near Arba Minch (old st.)	6.12	37.63	1184.64
Chamo	near Arba Minch	5.93	37.53	1116.17
Awassa	AWASSA	7.05	38.45	1685.74
Cheleleka	near Awassa	7.08	38.52	1686.85
Abaya	GIDICHO	6.40	37.95	1184.19

In order to evaluate the potential of water in each major lake, the topography of the lake bed should be known to calculate the volume of water. This work (bathymetric survey) has been done at some of the lakes. The dimensions of the major lakes are given below.

Table 1.6: Characteristics of Major Lakes

Lake name	Level Fluctuation Range (m)	Mean Depth (m)	Surface area (km^2)	Volume (Mm^3)	Surface elevation (m AMSL)
Ziway	2.07	2.5	440	1466	1636
Abiyata*	6.88	6	133	758	1581
Langano*	2.50	22	247	5555	1590
Shala*	NA	121	302	36472	1558
Abaya	3.06	7	1140	9818	1171
Chamo	3.28	12	335	4100	1110
Awassa	3.49	10.7	130	1300	1500

* Data from Halcrow 2008

Out of the major lakes in the table above, bathymetric survey has been conducted in Lake Ziway, Awassa, Abaya and Chamo by some Ethiopian government offices and universities by the year of 2005. The rest of the lakes were surveyed in the master plan study conducted by Halcrow 2008. The results of these new surveys are reflected in the table.

1.2 Collection and review of hydrometeorological data

The meteorological data, especially the temperature and precipitation, is used to grasp the meteorological characteristics of the Rift Valley Lakes Basin and the data, along with other sets of data, will be used to analyze water balance of the basin.

A set of daily meteorological data was collected from 70 Awassa and Adamaa branch offices of National Meteorological Service Agency (NMSA) and also from its head office. The data was supposed to cover all available stations in the study area and all available periods. However, the team found that there were strict regulations on the release (sale) of especially daily data in NMSA, which significantly hampered data collection of required number of station and required periods. Also monthly average meteorological data for 10 stations within and surroundings of the Rift Valley Lakes Basin was downloaded from the WMO website.

1.2.1 Meteorological data

Meteorological data was collected and analyzed in the master plan study conducted by Halcrow 2008. This report was reviewed in this study and the team identified the following general issues in the beginning.

1) The data coverage is limited to mid-late 2006 at the latest

2) Some of the existing stations were omitted for unknown reasons

3) The locations of stations employed for mapping are not very accurate

Further review and investigation revealed the following reasons for the issues above.

For issue 1, the data collection and hydro-meteorological analysis was mostly conducted in phase 1 of the Halcrow master plan study. Thus, it is natural that the maximum data coverage is up to the year 2006. In the review of data in this study, the newly collected recent data sets of up to the year 2010 will be evaluated for consistency with time.

For issue 2, it was found that not all data from “then available” stations were used for data review and analysis in Halcrow 2008. Clear reasons are unknown. In some areas, we found that some stations were newly established after 2006 and also relocated around that time. This may be one of the possible reasons for not having collected the data from these stations. In this study, of course, the data from such stations will be duly considered.

For issue 3, the locations of stations on the maps produced by Halcrow 2008 show some deviation from the points plotted using the original coordinate data obtained from NMSA in this study. This deviation is clear even on the 1.5 million scale maps and does occur for about 80% of the stations. The degree of deviation is usually within a few tens of kilometers and may not cause significant error in spatial analysis of this scale. Further investigation revealed that the reason for this deviation was unavailability of GPS coordinate data at the time of the Halcow master plan study. At the time, the locations of the stations were identified on topographic maps of 1:250,000 scale with village or town names as a clue and the coordinates were read off the map. Some of the major stations, however, seem to have been visited during the study to measure the coordinates. On the other hand, surveys of the locations of the stations were conducted only a few years ago and both branches now provide the list of stations with GPS coordinates information.

Another issue is that, in spite of the actual surveys conducted, the team found more than a few errors in that coordinates data obtained from NMSA. These errors may have happened while typing the data into the computer or during the conversion of original longitude and latitude coordinates data to the decimal system or to UTM. This may be another reason for the deviation of locations of stations discussed above. In this study the location data was carefully converted from the original data from NMSA to show the locations of stations as accurately as possible. The locations of stations that are apparently erroneous were also verified as much as possible. It should be noted that both branch offices of NMSA was re-surveying the location of the stations but not all the data was updated in this report.

a. Rainfall

The rainfall is the most basic parameter in the meteorological observation and is measured at stations of all classes. Thus, the data was obtained from all the 35 stations on the list. Most of the data obtained for the stations under Adamma branch starts from mid 90s and cover 15 years. Six out of the 17 stations only have the data for the last few years, which may not be very useful in the analysis. On the other hand, more than 20 years of data is available for 14 stations under Awassa branch.

b. Temperature

Temperature is measured as maximum and minimum temperatures at Class 1 and Class 3 stations. Thus the data set from a total of 25 stations are available at this moment However, three of them have data only for a few years, which may not by very useful in the analysis.

c. Other data

The parameters other than rainfall, maximum and minimum temperatures are the following four items and measured at only level 1 station.

1) Relative humidity, 2) Wind run, 3) Evaporation, 4) Sunshine

Thus the data sets from a total of 14 stations under Awassa branch are available for this reporting. Measurement of evaporation is not common even at class 1stations and consequently, useful pan evaporation data is only available for two stations, Awassa and Jinka.

1.2.2 Hydrological data

A set of hydrological data (daily lake level and monthly summary river discharge) was collected from the hydrology section of Ministry of Water and Energy (former Ministry of Water Resources). The data covered all the available stations (42 stations) in the study area and all available periods. The collected data was first reviewed for errors, missing periods and consistency. Then the data was further compared with the results of the Halcrow report. The location of the stations is shown in Figure 1.40.

The same issue of identification of locations of the stations was revealed in the case of hydrological data. According to the staff of the hydrology section, the locations of the stations were identified on a road map and their coordinates are read off the map in longitude and latitude system. Then the data was converted to UTM, as in the list. Recently, the Ministry started surveying the stations with GPS, but it had not covered those in the study area at the time of reporting. Consequently the obtained data includes some possible and apparent errors that were verified and corrected as much as possible in the study.

Another issue is the quality of data, especially of river discharge. This was pointed out in Halcow 2008 and also in Progress Report (1). Thus, the river discharge data is considered only as a rough indicator in this study. The lake level data, on the other hand, is relatively reliable and is more useful when recently surveyed bathymetric data is available in all the lakes. Only Lake Shalla lacks water level data because the staff gauge was quickly corroded after the setup due to waste water discharge from a nearby factory.

a. River flow

Monthly river flow data was collected for 33 stations. The data period mostly starts from the 80s and 90s and the average number of data years is 19.3 years. The average ratio of missing data is 13.3%. Some of the stations seem to be measuring a small stream from a nearby spring source because the measurement result is stable throughout the year.

b. Lake level

Lake level data was collected as both monthly data and daily data for eight stations.. The data period coverage is shorter in monthly data but the daily data coverage is mostly up to 2009. The average number of data years is 33.9 years and the average ratio of missing data is 10.1% for the daily data. This data, being more reliable than the monthly river discharge data, can provide good information on the amount of surface water drainage when combined with the bathymetric survey results.

1.3 Analysis of meteorological and hydrological data

1.3.1 Analysis of meteorological data

The meteorological conditions of a given wide and independent area affect the formation of water resources and consumption in that area more than other conditions. The following meteorological factors have influence on formation of water resources in the order of the arrangement.

1) Precipitation (rainfall)
2) Evapotranspiration
3) Other factors such as temperature

The collected data was analyzed in this order.

a. Analysis of rainfall

Because of its geographic characteristics of the rift valley lakes basin, there is no inflow of water from the other basins. There should be some water accumulated in underground reservoirs throughout the geological period but the amount is relatively small and it is not renewed. Thus, the use of such groundwater is viable, from the viewpoint of water balance and especially from the viewpoint of formulation of a water supply plan.

Under the natural circumstances, the surface and sub-surface water resources in a basin are created mostly by precipitation over the basin area. Thus, the amount and distribution of the precipitation in the basin determine the amount of surface water resources in the basin.

The following items were analyzed in accordance with the basic requirement of hydrological study to clarify the characteristics of rainfall in the rift valley lakes basin.

- Spatial distribution of precipitation
- Long term trend in change in rainfall amount
- Cyclic features and probability of precipitation

a.1 Data employed for analysis

Two kinds of data were collected for the analysis. One is the daily precipitation measurement record collected directly from the observation stations in the study area (70 stations) and the other is a set of monthly averaged data downloaded from WMO (World Metrological Organization) website (from 10 stations).

The information of each observation station such as its name, location, elevation, data source, and available data period is compiled in Table 1.7.

Table 1.7: Available Precipitation Data

Station Name	Easting	Northing	Ele(m)	Source	Duration	MD_1	MD_2
Abaya	382245	730806	1194	Original	2008 - 2010	20.8%	20.8%
Aje	428683	806427	1851	Original	1972 - 2010	47.0%	13.9%
Alba kulito	399984	808110	1779	Original	1989 - 2010	0.8%	0.8%
Aletawondo	435663	729916	1919	Original	1986 - 2010	1.1%	1.1%
Amarokele	377975	645265	1649	Original	1983 - 2010	12.4%	5.6%
Angacha	374299	812007	2315	Original	1982 - 2010	21.5%	12.5%
Aposto	430617	744523	1755	Original	1989 - 2010	6.5%	6.5%
Arata	506566	882329	1767	Original	1996 - 2010	2.2%	2.2%
Arbaminch	340804	670223	1213	Original	1974 - 2010	6.9%	1.5%
Arguba	323691	633185	1320	Original	2007 - 2010	0.0%	0.0%
Arsinegele	462834	812957	1917	Original	1958 - 2010	56.7%	28.4%
Assela	514692	878692	2440	Original	1996 - 2010	2.2%	2.2%
Awassa	442915	780888	1765	Original	1981 - 2010	0.1%	0.1%
Bedessa	382685	759469	1610	Original	1987 - 2010	0.2%	0.2%
Belela	435787	767294	1892	Original	1996 - 2010	10.1%	10.1%
Beto	265744	669646	1085	Original	1990 - 2009	6.2%	6.2%
Bilatetena	403434	766257	1502	Original	1973 - 2010	6.9%	4.4%
Billate	399204	754132	1360	Original	1980 - 2010	4.3%	4.3%
Bodity	373901	768994	2043	Original	1986 - 2010	0.3%	0.3%
Boreda	348799	715522	2272	Original	2008 - 2010	33.4%	33.4%
Buie	450951	920825	2059	Original	1987 - 2010	6.4%	2.3%
Bulbula	460886	853586	1685	Original	1967 - 2010	8.8%	6.7%
Burji	374596	606280	1818	Original	1956 - 2010	28.2%	15.9%
Butajira	431248	897824	2079	Original	1955 - 2010	26.0%	11.8%
Chencha	390391	688893	1624	Original	1989 - 2010	10.5%	6.3%
Dadim	396250	557794	1763	Original	1990 - 2010	16.5%	16.5%
Degaga	482393	821655	2079	Original	1969 - 2010	37.8%	15.8%
Derara	422798	757163	1901	Original	1989 - 2010	3.6%	3.6%
Dilla	423349	705247	1524	Original	1954 - 2010	43.9%	22.1%
Doyogena	360000	701100	1368	Original	2009 - 2010	32.4%	32.4%
Ejersalele	465617	911842	1803	Original	1967 - 2010	7.7%	5.5%
Erbore	467446	868624	1685	Original	1987 - 2009	6.8%	6.8%
Fonko	386297	845480	2238	Original	1986 - 2010	2.7%	2.7%
Gato	324403	614371	1294	Original	1973 - 2010	3.0%	3.0%
Gedeb	416292	653210	2249	Original	1981 - 2010	9.2%	6.0%
Geresse	312134	654714	2375	Original	1992 - 2010	12.0%	12.0%
Gumaide	339137	617631	1619	Original	1976 - 2010	4.0%	4.0%
Hageremariam	415094	622671	1860	Original	1984 - 2010	11.0%	11.0%
Hossana	373808	836608	2311	Original	1981 - 2010	10.6%	4.3%
Humbotebela	363569	741036	1625	Original	1987 - 2010	8.0%	8.0%
Jinka	239689	624984	1415	Original	1981 - 2010	3.5%	3.5%
Kamba	297493	670056	1891	Original	1987 - 2010	8.4%	4.4%

Station Name	Easting	Northing	Ele(m)	Source	Duration	MD_1	MD_2
Kawakoto_Alicho	413712	885607	3145	Original	2007 - 2010	21.8%	21.8%
Kebado	427614	711106	1842	Original	1990 - 2010	3.3%	3.3%
Keyafer	248987	610809	1614	Original	1985 - 2010	14.1%	10.6%
Kolme	306929	588510	1533	Original	1976 - 2010	5.7%	2.9%
Konso	326951	590748	1421	Original	1984 - 2010	8.9%	8.9%
Koshe	448353	885441	1877	Original	1974 - 2010	3.9%	3.9%
Kulumsa	517524	886023	2212	Original	1996 - 2010	2.9%	2.9%
Kuyera	461890	806473	1933	Original	1951 - 2010	47.4%	21.1%
Langano	465185	834140	1685	Original	1981 - 2010	13.2%	13.2%
Meki	479868	900993	1685	Original	1980 - 2010	12.0%	6.0%
Mirababaya	364002	695383	1221	Original	1982 - 2010	3.2%	3.2%
Ogolcho	501650	888550	1697	Original	1996 - 2010	10.6%	4.2%
Sankura	409230	834879	1874	Original	2006 - 2010	38.7%	38.7%
Shone	384545	788590	1964	Original	1973 - 2010	3.2%	3.2%
Shshemene	455884	795851	1934	Original	1981 - 2010	7.6%	7.6%
Sire	498156	799470	2875	Original	1996 - 2010	0.6%	0.6%
Teltele	443000	755250	1906	Original	1969 - 2010	50.4%	13.2%
Tora	436446	868696	2011	Original	1974 - 2010	5.7%	5.7%
Wajifo	360848	713703	1238	Original	1979 - 2010	45.1%	23.7%
Werabe	465253	764638	2685	Original	2006 - 2010	15.9%	15.9%
Weteraressa	411394	867807	2045	Original	2004 - 2010	22.3%	22.3%
Woito	278326	593128	582	Original	2004 - 2010	1.2%	1.2%
Wolaitasodo	361754	754133	1865	Original	1981 - 2010	2.3%	2.3%
Wondogenet	457547	782775	1765	Original	1970 - 2010	8.3%	6.0%
Wulberg	403265	855389	1992	Original	1972 - 2010	5.6%	5.6%
Yabelo	393369	578229	1762	Original	1987 - 2010	2.3%	2.3%
Yirgachefe	412391	679930	1909	Original	1986 - 2010	11.1%	11.1%
Zeway	468560	877212	1685	Original	1982 - 2010	4.8%	4.8%
Abonsa	380200	798700	2128	WMO	1965 - 1976	15.3%	15.3%
Adamitulu	469823	886464	1663	WMO	1908 - 1989	52.7%	5.5%
Bokoji-Farm	527407	832179	2782	WMO	1971 - 1984	12.5%	12.5%
Durame	377700	800000	2077	WMO	1973 - 1984	8.3%	8.3%
Gidole	318278	624579	2178	WMO	1954 - 1971	35.2%	16.7%
Jinka Bacco	228681	641683	1413	WMO	1970 - 1984	7.8%	7.8%
Kella	444472	912526	1921	WMO	1972 - 1984	0.6%	0.6%
Kofelle	476356	782064	2679	WMO	1955 - 1982	23.8%	14.7%
Kore	492305	797928	2773	WMO	1968 - 1984	7.8%	7.8%

Easting & Northing: Coordinate of precipitation observation station in projection Adindan UTM zone 37N.
Ele: Elevation of the station (mamsl)
MD_1: Percentage of missing data for the whole observation years.
MD_2: Percentage of missing data except those years without any observation data.

The locations of the stations (Table 1.7) from which precipitation data was collected, are shown on the map in Figure 1.6.

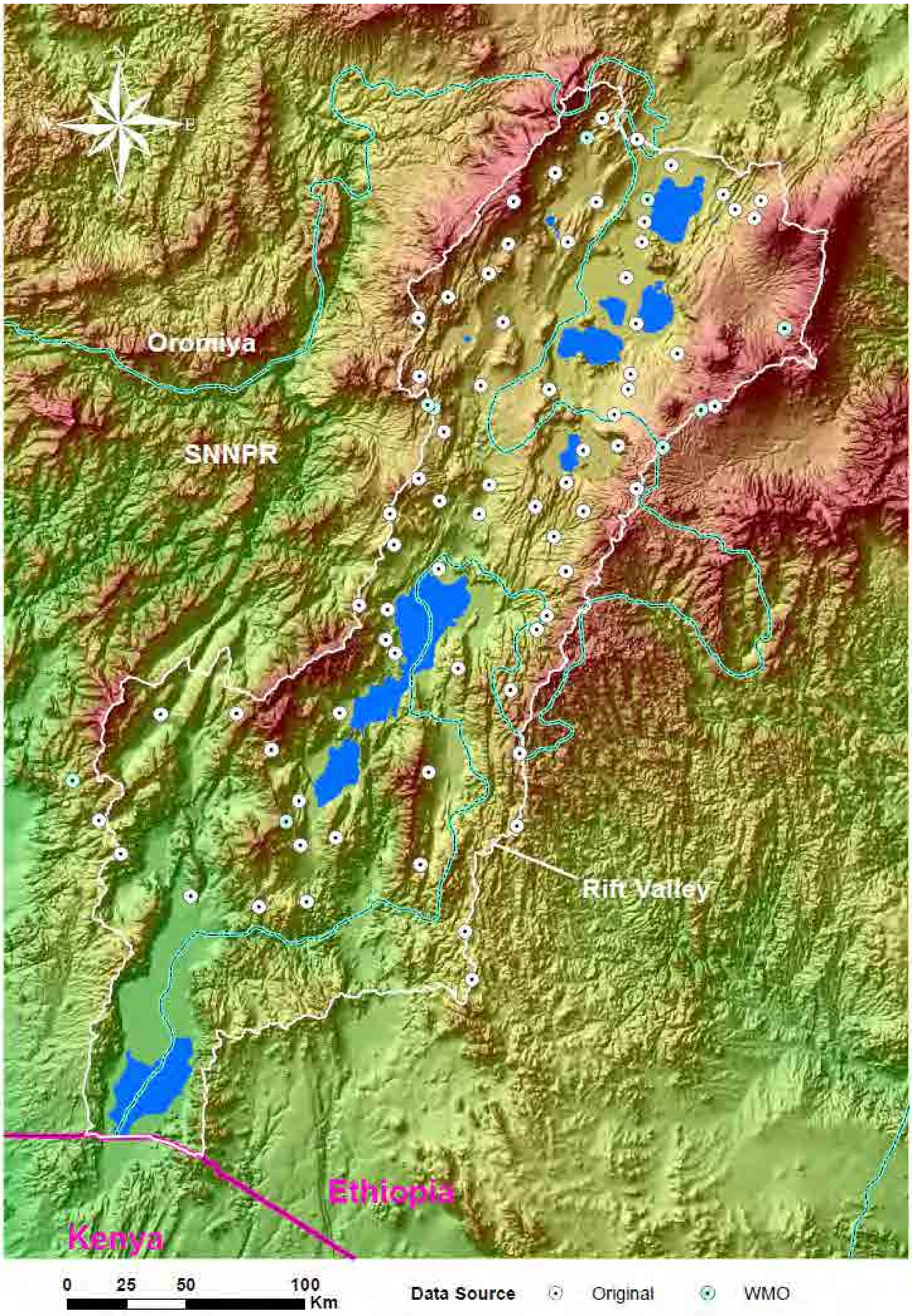


Figure 1.6: Location of Stations Used for Precipitation Analysis

a.2 Complementation of precipitation data

Errors and data absence occur in meteorological measurements due to the use of faulty measurement devices etc. If such errors were used without verification, there would be a risk of introducing an error also in the analysis result and would lead to underestimation of precipitation.

Therefore, the collected data was verified before analysis and the apparent errors found were all corrected as shown in the following examples.

Buie Station : The data for 2008/06/18 is given as 5.2.7mm. This is apparently an input error and either of the decimal points had to be removed. When the data was compared with the data from the previous and following days, they were 0 and 20.7 respectively. Thus the data should be 5.27 mm.

Arbaminch Station : The data for 1979/09/15 is given as 0.013mm. No other data is measured to this accuracy and thus, the value was corrected as 1.3mm.

Zeway Station : The for 2008/11/02 is given as 142..5mm. This was considered a simple input error and the value was corrected as 142.5mm.

Is important to check the data prior to analysis as described above but complementing the missed data is also very important.

The data sets from all the stations except for Awassa stations have some missing data periods as shown in Table 1.7. For example, the data is missing for almost half of the observation period at Dilla station.

Data missing happens throughout a year, or monthly or daily levels. If it is for a whole year, it is usually better and easier to simply eliminate that year for analysis. If the missing period is from a few days to a few months, the data can not be, precisely speaking, restored. However, discarding the data set that have the missing period in some cases leads to insufficient data amount for the analysis.

Therefore, such missing data should be complemented as much as possible. In this analysis, the auto correlation method was used to complement the data. The method estimate the missing data based on the averaged daily values from each observation station for the period from 1st January to 31st December. It is expressed in the following formula.

$$\mathbf{R_i = \Sigma R_j / N}$$

Whereas

R_i : Complemented value of missed data of a day

ΣR_j is the sum of the precipitation value of a day from different years recorded at a station where some data is missing

N is the number of years (or days) for which observation was conducted

The hydrological parameters usually show periodical changes in their values affected by various conditions. The period of such change (cycles) can be from a few years to a few tens of years. Therefore, if the available data period is short, the analysis can not detect such a cycle and thus will result in values for either dry year or wet year. Thus, only the data sets that cover 10-year period or more were used for the analysis.

The sets of precipitation data complemented by auto-correlation method are presented in Table 1.8.

Table 1.8: Result of Precipitation Data Supplement

Station Name	O_Years	R_Years	O_Data	S_Data	Pcnt
Aje	39	34	17,795	20,659	16.1%
Alaba kulito	22	22	21,730	21,827	0.4%
Alem Tena	15	15	12,242	12,392	1.2%
Aletawondo	25	25	39,240	39,424	0.5%
Amarokele	28	26	24,381	25,266	3.6%
Angacha	29	26	35,130	40,070	14.1%
Aposto	22	22	23,099	24,583	6.4%
Arata	15	15	11,725	11,830	0.9%
Arbaminch	37	35	30,380	30,791	1.4%
Arbegona	19	16	12,695	15,588	22.8%
Arsinegele	53	32	21,663	29,689	37.1%
Assela	15	15	16,276	16,549	1.7%
Awassa	30	30	29,049	29,066	0.1%
Bedessa	24	24	26,558	26,624	0.3%
Belela	15	15	14,179	15,590	9.9%
Beto	20	20	19,098	20,354	6.6%
Bilatetena	38	37	32,878	34,308	4.4%
Billate	31	31	23,636	24,598	4.1%
Bodity	25	25	30,899	30,952	0.2%
Buie	24	23	23,893	24,389	2.1%
Bulbula	44	43	26,288	28,614	8.8%
Burji	55	47	36,594	43,148	17.9%
Butajira	56	47	45,685	51,169	12.0%
Chencha	22	21	26,782	28,418	6.1%
Dadim	21	21	11,702	13,841	18.3%
Degaga	42	31	28,319	33,675	18.9%
Derara	22	22	26,098	26,888	3.0%
Dilla	57	41	41,971	54,087	28.9%
Ejersalele	44	43	33,656	35,335	5.0%
Erbore	23	23	10,654	11,307	6.1%
Fonko	25	25	30,469	31,441	3.2%
Gato	38	38	32,981	34,012	3.1%
Gedeb	30	29	41,001	42,859	4.5%
Geresse	19	19	35,600	40,642	14.2%
Gumaide	35	35	31,303	32,474	3.7%
Hageremariam	27	27	22,148	24,445	10.4%
Hossa	30	28	32,128	33,418	4.0%
Humbotebela	24	24	25,211	27,226	8.0%
Jinka	30	30	37,063	38,326	3.4%
Kamba	24	23	30,676	32,061	4.5%
Kebado	21	21	28,845	29,734	3.1%
Keyafer	26	25	27,112	30,382	12.1%

Station Name	O_Years	R_Years	O_Data	S_Data	Pcnt
Kolme	35	34	28,483	29,023	1.9%
Konso	27	27	19,063	20,990	10.1%
Koshe	37	37	33,308	34,256	2.8%
Kulumsa	15	15	12,054	12,437	3.2%
Kuyera	60	40	28,803	36,940	28.2%
Langano	30	30	20,210	23,306	15.3%
Meki	31	29	20,490	21,309	4.0%
Mirababaya	29	29	20,014	20,655	3.2%
Ogolcho	15	14	9,515	9,907	4.1%
Shone	38	38	56,103	57,721	2.9%
Shshemene	30	30	23,140	25,059	8.3%
Sire	15	15	13,581	13,594	0.1%
Teltele	42	24	14,756	17,070	15.7%
Tora	37	37	31,303	33,097	5.7%
Wajifo	32	23	18,386	23,703	28.9%
Wolaitasodo	30	30	37,812	38,910	2.9%
Wondogenet	41	40	42,535	45,406	6.7%
Wulberg	39	39	46,507	49,214	5.8%
Yabelo	24	24	14,294	14,551	1.8%
Yirgachefe	25	25	30,741	34,849	13.4%
Zeway	29	29	20,654	21,454	3.9%
Abonsa	12	12	12780	13105	2.5%
Adamitulu	72	32	24181	24515	1.4%
Bokoji-Farm	14	14	12418	14141	13.9%
Durame	12	12	11840	12746	7.7%
Gidole	18	14	13719	16276	18.6%
Jinka Bacco	15	15	18932	20359	7.5%
Kella	13	13	16494	16494	0.0%
Kofelle	26	24	25678	29603	15.3%
Kore	17	17	18214	19744	8.4%

O_years: Observation years (duration from the first year to the last years of the observation)
Real_years: The real observation years (observation duration without missing years).
O_Data: Original data in unit of mm for the real years.
S_Data: Supplemented data in unit of mm for the real years.
Pcnt: Percentage of the supplement result to the original data.

a.3 Average precipitation

Amount of precipitation changes every year: some years have more rain and others less. The hydrological conditions that will be important depend on the purpose of water resources study. If the study is for flood control, the precipitation amount for wet years and if the study is for water resources evaluation or preventing excessive drawdown of groundwater, the data for dry years will carry more importance. On the other hand, average precipitation amount will be important for the purpose of understanding the general characteristics of water resources amount in a given area.

The average annual precipitation, maximum and minimum annual precipitation for each observation stations in the rift valley basin have been compiled based on the data that were complemented. Table 1.9 and Figure 1.7 show the analysis result from the 72 stations (Original daily: 62 stations, WMO: 10 stations).

Table 1.9: Summary of Precipitation in Rift Valley Area

Station Name	Average	Max	Year	Min	Year
Aje	2,582	5,215	1982	1,111	1987
Alaba kulito	992	1,261	1993	763	1999
Alem Tena	826	1,042	2008	589	2002
Aletawondo	1,577	2,079	2007	1,236	1999
Amarokele	972	1,497	1988	672	2008
Angacha	1,541	2,408	2001	949	1994
Aposto	1,117	1,517	1989	675	1999
Arata	789	1,042	2010	575	2002
Arbaminch	880	1,283	1997	572	1976
Arbegona	866	1,319	1998	479	1991
Arsinegele	928	1,487	2004	539	2009
Assela	1,103	1,439	2001	780	2002
Awassa	969	1,198	2006	704	2009
Bedessa	1,109	1,347	2001	712	1999
Belela	1,039	1,612	2010	559	2009
Beto	1,018	1,525	2006	494	1999
Bilatetena	927	1,344	1996	406	1984
Billate	793	1,111	2010	493	1999
Bodity	1,238	1,540	1998	952	2000
Buie	1,060	1,518	2010	759	1994
Bulbula	665	999	1989	355	1971
Burji	918	1,267	1972	628	1999
Butajira	1,089	1,783	2005	513	2009
Chencha	1,353	2,355	1997	757	2004
Dadim	659	952	2010	399	1999
Degaga	1,086	1,354	1996	821	2004
Derara	1,222	2,579	1992	823	1999
Dilla	1,319	1,755	1958	950	1961
Ejersalele	822	1,263	1996	438	2002
Erbore	492	934	1997	211	1999
Fonko	1,258	1,665	1997	892	1994
Gato	895	1,740	1982	481	1975
Gedeb	1,478	2,873	1996	914	2004
Geresse	2,139	3,991	1996	1,163	2002
Gumaide	928	1,614	1989	533	2000
Hageremariam	905	1,467	1987	509	1995
Hossa	1,194	1,624	1982	846	1981
Humbotebela	1,134	1,854	1996	680	1991

Station Name	Average	Max	Year	Min	Year
Jinka	1,278	1,747	1989	812	1985
Kamba	1,394	1,683	2010	1,096	1991
Kebado	1,416	1,767	1996	1,009	1991
Keyafer	1,215	2,323	1997	724	1994
Kolme	854	1,255	2006	438	1980
Konso	777	1,006	2001	452	2000
Koshe	926	1,780	1983	508	2009
Kulumsa	829	955	2008	708	2002
Kuyera	923	2,644	2008	521	1966
Langano	777	1,603	2010	465	1991
Meki	735	1,145	1983	387	1995
Mirababaya	712	1,217	1997	397	1992
Ogolcho	708	825	2010	544	2005
Shone	1,519	2,463	1997	938	1984
Shshemene	835	1,241	1982	402	2009
Sire	906	1,123	1998	534	2002
Teltele	711	976	1997	478	1976
Tora	895	1,246	1993	499	1984
Wajifo	2,061	3,886	2006	962	1984
Wolaitasodo	1,297	2,788	1981	312	1986
Wondogenet	1,135	1,447	1997	688	2009
Wulberg	1,262	2,196	1979	672	1981
Yabelo	606	874	2004	372	1999
Yirgachefe	1,394	2,130	1996	964	1998
Zeway	740	960	1989	482	2002
Abonsa	1,092	1408	1967	884	1974
Adamitulu	597	962	1977	368	1932
Bokoji-Farm	1,011	1439	1977	737	1984
Durame	1,062	1595	1977	657	1984
Gidole	1,163	1729	1961	934	1957
Jinka Bacco	1,357	1957	1977	888	1980
Kella	1,268	1734	1977	833	1984
Kofelle	1,184	1463	1982	969	1955
Kore	1,161	1568	1983	856	1984

The result of analyses for the average annual rainfall amount shows that the values range from 492mm to 2,582mm, showing 5-fold difference that is considered large. The simple average of the 72 stations in the rift valley basin is 1,079mm.

Since the data periods covered largely differ from station to station, the maximum and minimum precipitations naturally appear in different years. However, the maximum annual precipitations occur in 1997 (for 9 stations), and in 2010 (for 8 stations), and the minimum annual precipitations occur in 1999 (for 11 stations) and in 1984 and 2002 (8 stations respectively) as long as the collected data can reveal. The largest and smallest annual rainfalls recorded were 5,152mm (Aje station), 211mm (Erbore station), showing

20 times difference. The difference between the maximum and minimum precipitation from the data of a single station range from 247mm (Kulumsaa station) to 4104mm (Aje station). In terms of the ratio, it is within the range of 1.34 (Kulmusa) to 8.94 (Wolaita Sodo station).

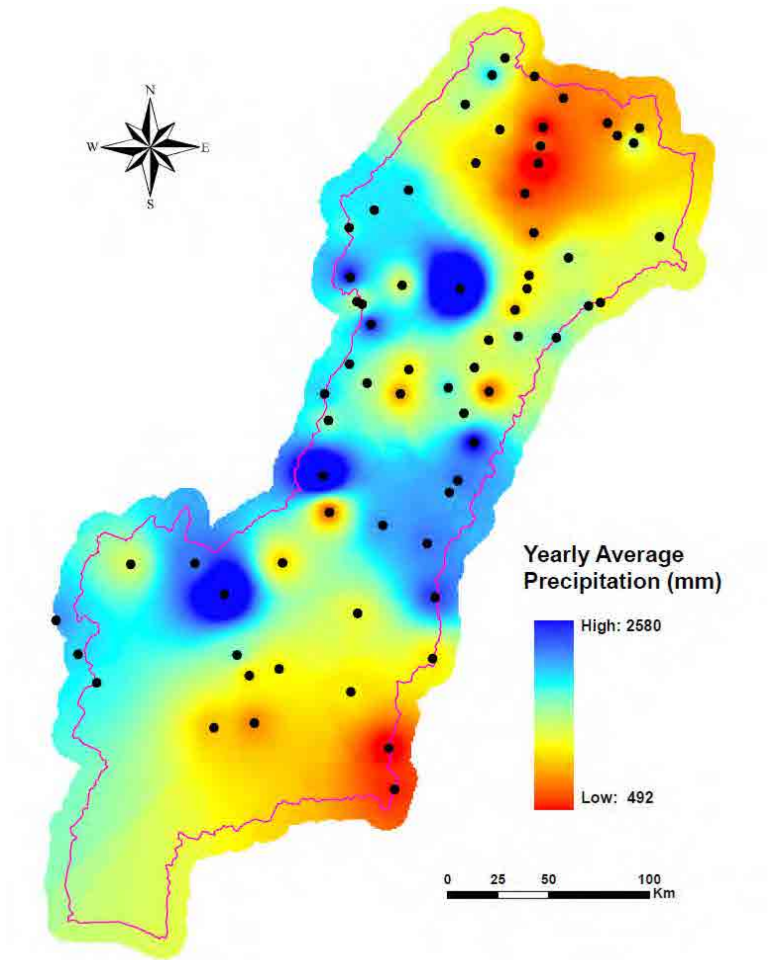


Figure 1.7: Distribution of Annual Average Precipitation in Rift Valley Area

a.4 Relation between altitude and precipitation

One of the characteristics of the rift valley lakes basin is its variation in surface topography. It is well known that the topography of an area affects precipitation amount. From that point of view, the relation between topography (altitude of stations) and annual average precipitation were plotted against a graph to examine the correlation between the two. Figure 1.8 shows slight tendency of increasing precipitation with altitude but no clear relation was recognized in the analysis.

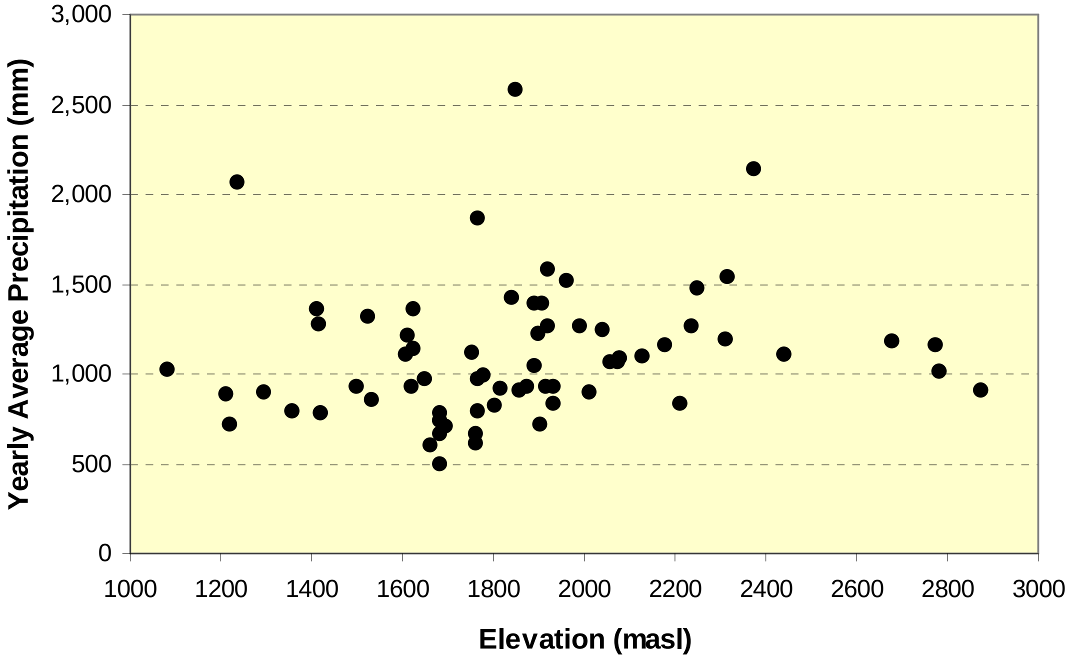


Figure 1.8: Relation between Precipitation and Elevation

a.5 Geographical distribution of precipitation

The area of the rift valley lakes basin is over 53,000km^2 and if the simple annual average precipitation amount is applied to the whole area, there will be a risk of introducing a large error in local precipitation within the basin. Meanwhile, the rift valley area is subdivided into sub-basins. If divided into small basins of their area between 100km^2～2,500 km^2 , the number will be 80 and if divided into large basins of their area between 1,000km^2～13,000km^2 , the number will be 14.

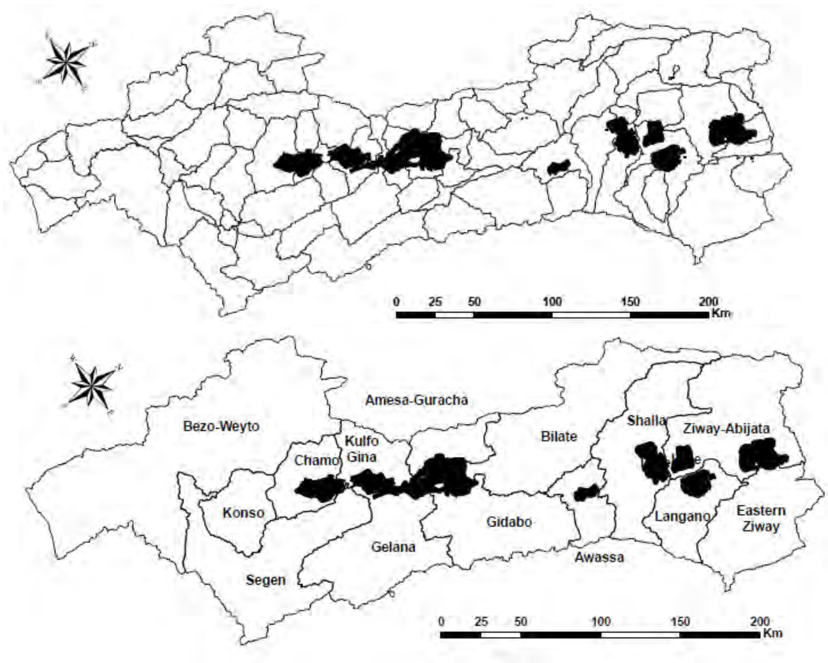


Figure 1.9: Divisions of Study Area by small (above) and large (bottom) sub-basins

There are many methods to calculate the annual average rainfall amount for each sub-basin. If there is a clear correlation between the topography and precipitation, a contour map of precipitation in consideration of the topography can be created to find the total amount of precipitation for each sub-basin with relatively high level of accuracy. However, in the case of the study area, such relation was not recognized as discussed earlier. Therefore, the Thiessen method, a common method used to analyze spatial distribution of precipitation, was employed to find the areas to which the of precipitation values of each observation station.

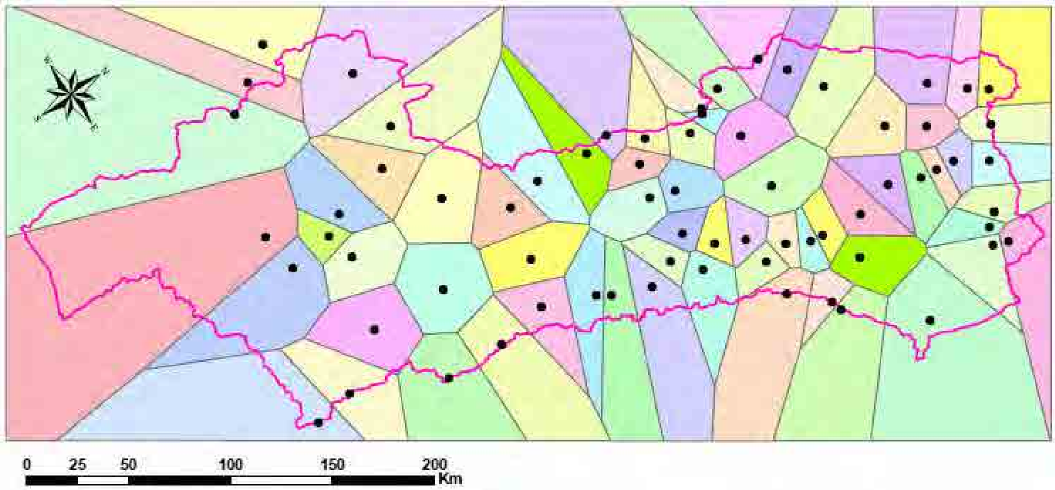


Figure 1.10: Thiessen Division of Annual Average Precipitation

Then, based on the Thiessen division, the total annual precipitation amount (T_rain in table below) over each large sub-basin was calculated by multiplying the area of sub-basin (Area in table below) by the precipitation value (A_rain in table below). The result is shown in Table 1.10.

Table 1.10: Summary of Precipitation in Sub-basin of Rift Valley

Sub_Basin	Area(km^2)	A_rain(mm)	T_rain(Mm^3)
Amesa-Guracha	1,797	1,537	2,761
Bezo-Weyto	12,143	1,104	13,406
Bilate	5,418	1,165	6,312
Eastern Ziway	3,435	966	3,318
Gelana	3,856	1,140	4,396
Gidabo	3,491	1,244	4,343
Konso Localized	1,685	851	1,434
Kulfo Gina	1,750	878	1,537
Lake Awassa	1,295	1,135	1,470
Lake Langano	2,059	920	1,895
Lake Shalla	4,054	1,453	5,891
Segen Watershed	5,230	815	4,263
Sile-Chamo	1,752	1,330	2,330
Western Ziway-Abijata	5,011	854	4,279
Total	**52,976**	**1,088**	**57,635**

A_rain: Annual average precipitation.
T_rain: Annual total precipitation.

Figure 1.11 shows average annual total precipitation amount (Mm^3) of the large sub-basins. The solid rectangles represent the total amount of precipitation with its averaged values on top of it in blue and the total amount over the area in purple below the rectangle. The higher the rectable, the mrore the total amount of rain in the sub-basin receives. The darkness of the color of the sub-basin also corresponds to the value of the total amount of precipitation: the darker the color, the greater the value. Since the total amount of precipitation in a basin is determined by multiplying the area the basin by the precipitation that falls over the basin. Thus, Bezo-Wayto sub-basin located at the southern most end of the study area, having the largest area and moderate precipitation value turned out to have the greatest total rain amount among all the sub-basins. The result shows that the distribution of rainfall amount (volume) is as shown in the figure above.

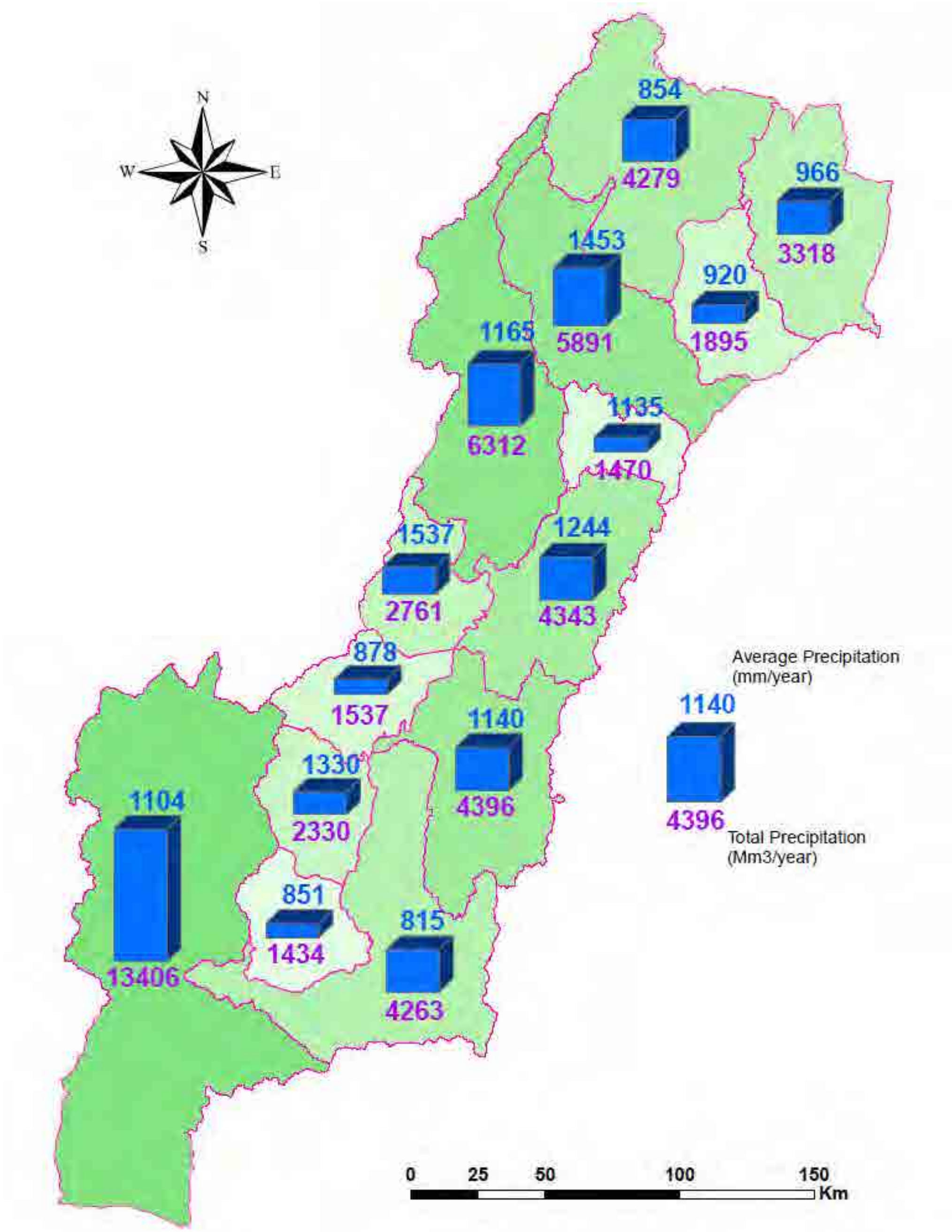


Figure 1.11: Distribution of Precipitation over Sub-basins in the Rift Valley Lakes Basin

a.6 Seasonal variation in precipitation

Table 1.11 is the compilation of monthly average precipitation for the 72 stations in the rift valley lakes basin.

Table 1.11: Monthly Average Precipitation Based on Supplement Data

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abonsa	34	57.5	93.6	125	103	85.5	159	168	125	60.5	47.4	6.9
Adamitulu	12.4	30.8	38.3	56.2	64.9	65.9	113	101	79.4	17.8	5.5	4.3
Aje	20.7	30.7	80.5	88.9	133	83.8	115	112	117	57.3	9.6	12.8
Alaba kulito	37.8	50.1	94.2	144	115	90.7	113	115	106	71.7	28.8	27
Alem Tena	24	15.7	66.4	68.6	54.2	95.4	197	159	88.6	36.3	14.4	6.1
Aletawondo	42.5	52.1	115	222	213	149	138	150	218	181	60.5	37.1
Amarokele	18.8	29.3	73.5	190	162	61.1	45.7	64.5	90.9	146	69.2	22.5
Angacha	41.3	70.9	117	184	170	166	194	211	191	114	50.9	32.9
Aposto	33.9	46.4	102	164	145	103	97	87.8	133	133	36.9	35.7
Arata	14.3	24.9	59.2	77.9	85.7	103	134	113	102	46.3	18.4	10.5
Arbaminch	30.4	33.9	61.8	150	152	62.1	45.9	49	83.9	115	59.7	37.5
Arbegona	38.2	39.1	75.9	113	90.5	81.8	88.4	86.2	85.7	92.4	40.1	36.6
Arsinegele	20.1	33.8	76.4	88.8	98.3	97.8	165	146	131	50.3	9.7	10.6
Asela	22.8	54.2	93.6	105	129	141	223	243	191	58.9	21.5	9.9
Awassa	29.1	41.2	80.5	111	119	105	121	118	123	72	30.8	22.1
Bedessa	39.6	41.6	90.4	156	153	120	119	119	87.3	110	43.7	29.4
Belela	35.8	31.4	85.1	152	130	86.2	97.4	99.4	126	127	47	23
Beto	57.5	27.5	102	139	127	63.6	54.7	64.3	83.7	145	91.5	61
Bilatetena	32.1	36.5	88.8	129	109	83.8	108	96.8	91.9	95.3	36.5	21.7
Billate	31.7	34.5	60.2	112	110	75	88.7	70.3	71.5	73	38.9	29.4
Bodity	29.6	55.8	96.1	164	167	130	150	160	122	87.5	38.9	39.8
Bokoji-Farm	29.6	42.8	75.5	80.6	100	114	199	174	90.6	55.1	19.3	10
Buie	23.9	59	94.2	91.5	76.6	127	221	200	105	36.8	14.1	9.9
Bulbula	15.8	29.2	48.2	71.3	66.2	76.7	128	105	71.9	38.7	10.8	4.6
Burji	31.6	29.3	90.4	170	149	42.2	37	34.7	73.1	154	76.5	31.3
Butagira	32.2	67.8	107	91.3	130	92.7	158	163	113	41.3	17.3	10
Chencha	55.2	52.3	129	192	148	89	120	119	132	168	84.4	65.8
Dadim	16	26.9	71.4	158	112	15.8	11	17.2	37.4	101	72.2	20.8
Dangla	4.3	4.5	26.4	46.5	103	226	334	322	214	90.1	50.7	9.7
Derara	45.3	53.9	111	182	153	101	102	105	151	139	44.4	35.3
Dilla	41	42.9	104	194	182	113	106	109	152	162	72.4	36.1
Durame	43.6	24.3	91.3	87.1	138	88.4	136	161	130	81.1	37.3	12.6
Ejersalele	16.6	39.7	60.4	73.2	63.7	85.9	194	164	86.7	25.6	11.4	3.1
Erbore	25.9	25.7	53.2	105	68.8	35.7	16.7	13.2	19.6	53.9	48.3	28.7
Fonko	30.4	50.6	121	156	140	125	170	178	152	93.2	17	24.4
Gatto	29.5	51.5	116	174	169	48.2	43.3	61.8	117	89.3	127	18.6
Gedeb	34.9	42.7	121	239	254	118	83.5	96.2	135	237	91.9	25.6
Geresse	59.7	53.9	133	393	351	191	181	169	198	240	107	64.6

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gidole	28.7	71.6	115	173	123	77.2	73.7	110	95	198	69.4	56.3
Gumaide	43.5	39.5	75.5	187	137	44.7	37.7	37	71.6	117	94	43
Hagere Mariam	14.7	26.6	76.2	152	184	48.6	44.5	23.6	56.5	135	46.7	13.9
Hossa	30.5	51.7	108	142	144	119	151	175	151	82.8	21.9	18.2
Humbotebela	35.1	34.1	66.2	140	147	128	155	154	92	99	42.1	43.6
Jinka	51.8	48.2	116	176	161	105	91.7	85.5	109	152	113	70.7
Jinka Bacco	38.6	70	106	180	167	107	102	121	133	168	126	32.8
Kamba	43.9	56.7	117	204	210	119	93.1	118	147	180	65.2	41.1
Kebado	40.8	50	110	213	226	117	89	117	179	183	50.3	41.4
Kella	36.4	55.5	85.9	103	120	149	238	226	144	57.8	16	5.2
Keyafer	56.3	44.5	133	190	147	86.9	64.2	79.8	95.2	134	104	80.5
Kofelle	40.3	59.6	117	140	89	108	147	151	143	93.9	56.2	24.5
Kolme	30.1	45.8	96.3	180	118	41	17.8	31.4	61.2	114	82.3	38.3
Konso	26	35.2	86.4	178	111	35.7	21.2	34.2	58.9	94.8	55.5	40.6
Kore	39.3	57.6	101	111	114	89.7	177	182	138	83.5	29	22.6
Koshe	27.9	49.2	86.2	94.9	124	99.5	197	225	132	58.4	9.1	0.3
Kulumsa	24.2	28.9	91.5	81.6	88.3	102	120	129	90.7	52.6	13.5	7.1
Kuyera	18.8	33.6	65.9	98.5	104	96.3	119	110	130	72.1	24.1	10.5
Langano	14.2	29.2	46.6	81.2	81.1	87	147	125	93.7	50.2	14.3	6.7
Meki	8.8	41.2	60.1	65	67.1	60.9	168	151	74.6	27.9	4.1	5.9
Mirababaya	25.2	24.9	54.7	105	110	69.9	50.8	52.8	56.1	75.9	55.8	31.7
Ogolcho	14	20.7	63.9	63.3	67	84.5	137	110	93.6	38.4	11.3	3.6
Shone	54.9	74.3	130	181	175	139	185	206	183	108	47.6	38.3
Shshemene	23.2	33.5	75.5	121	104	66.2	98.1	92	112	71.7	21.9	16.1
Sibu Sire	14.9	22.3	55.1	82.5	146	220	267	248	176	71.8	33.6	15.6
Teltele	39.8	33.3	103	150	110	14.8	15	14.2	34.1	109	62.7	28.5
Tora	23.1	46.2	77.1	113	103	85.9	137	123	118	52.1	10.2	6.6
Wajifo	21.2	25.2	76.3	143	148	94.2	122	147	70.2	92.1	56.8	39.9
Wolaitasodo	30.7	42.9	81.1	163	183	131	180	188	112	90	56.1	39.2
Wondogenet	30.1	49.9	108	136	123	106	138	143	145	106	32.1	20.6
Wulberg	30.5	53.2	96.8	121	143	148	211	196	165	69.5	17.7	11.1
Yabelo	23.1	27.4	84.9	148	92.9	12.3	10.6	9	34	94.8	48.5	21.2
Yirgachefe	26.9	37	93.9	255	242	105	79.6	103	147	208	79.1	43.5
Zeway	17.6	34.9	51.9	72.8	76.4	79.6	152	121	75.7	40.5	11.9	5.8
Maximum	**60**	**74**	**133**	**393**	**351**	**226**	**334**	**322**	**218**	**240**	**127**	**81**
Minimum	**4**	**5**	**26**	**47**	**54**	**12**	**11**	**9**	**20**	**18**	**4**	**0**
Average	**31**	**42**	**90**	**143**	**136**	**95**	**121**	**123**	**112**	**103**	**49**	**27**

For Information on the seasonal variation of precipitation in the rift valley area and that covering the entire Ethiopia was compared. The following data was used for the comparison:

- Daily precipitation data from 62 observation stations and the sets of monthly data downloaded from WMO website (10 stations)
- For Ethiopia, sets of monthly data from 123 stations over the country downloaded

from WMO website

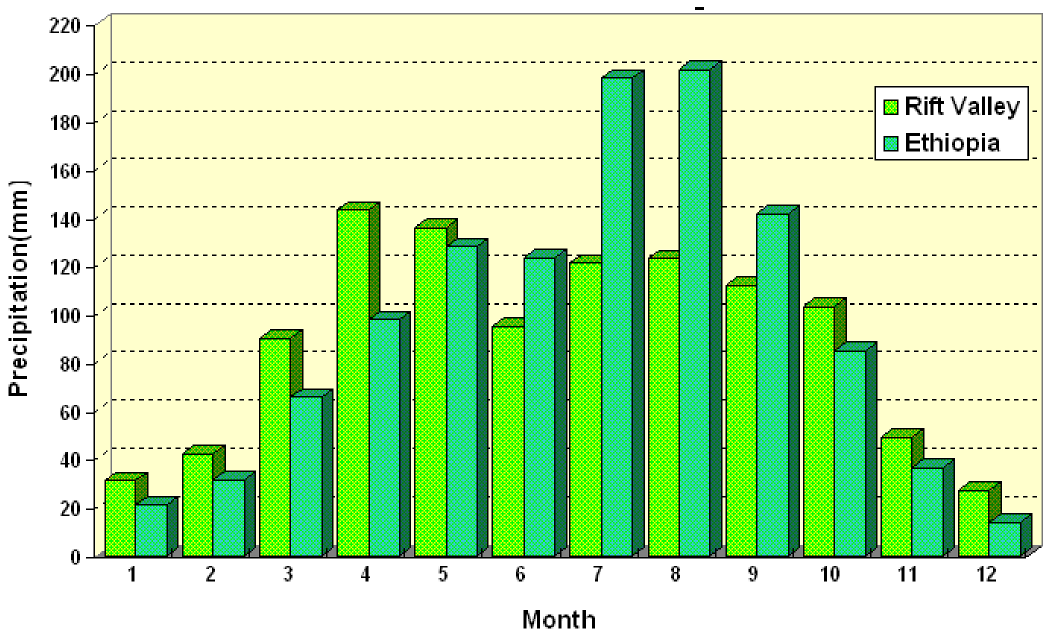


Figure 1.12: Comparison of Annual Precipitation Pattern between the Rift Valley Basin and Entire Ethiopia

As shown in Table 1.11 and Figure 1.12, there is a distinction of rainy season and dry season in the rift valley lakes basin. The rainy season starts from March and ends in October in general (eight months) while the dry season starts from November and continues up to February. The rainy season further has two peaks in April and August.

In comparison with the annual precipitation pattern for the entire Ethiopia, that of Rift Valley Lakes Basin was found to be characterized by smaller difference in the amount of precipitation between wet and dry seasons and by the two peaks in precipitation during the wet season.

a.7 Trend of precipitation change

In this section, the data will be analyzed to examine how the precipitation amount tends to change over a long period of time. Analysis of hydrological parameters for long term hydrological cycles is one of the important items in long-term water resources management. In the analysis of hydrological cycles, the longer the data period, the more accurate the result of the analysis becomes. The longest data period among the obtained data sets is of Adami tuul station from the WMO database. It covers a period of 82 years from 1908 to 1989. However, date for a period of 27 years from 1938 to 1973 is missing data. Also the end of observation is as old as 1989 20 years before the beginning of this study (2010). Both features pose some problem in the analysis of the data.

As explained earlier, there are several methods of data complementation that are available. However, if the auto-correlation method is used, all the missing data for a long period of non-observation will be filled by averaged data and will not be appropriate for analysis of hydrological trends. Thus, the data complementation was conducted by comparing the data with the data sets from the surrounding stations using the relation between geographical proximity and hydrological characteristics.

In this context, the relation between the data from Adami tuul station and other 3 stations that have relatively long period of observed data in the rift valley area, were compared for their relationship. The analysis revealed that the correlation coefficients among them fall within the range of 01 to 0.6 and thus, no clear correlation was recognized. Thus, this method can not be used to complement the data. The analytical results of the data from the four stations are shown in Figure 1.13 and Figure 1.14.

As can been seen in Figure 1.13, the precipitation data for Kuyera station for the year 2008 is much larger than the values of the other stations. The probability analysis of precipitation indicates that a precipitation amount of that magnitude can only occur once in 50,000 years. It is considered abnormal to have such an extremely high value of precipitation when all the other stations have values within the normal range. For this reason, the data of this year was excluded from the analysis. The result is then shown in Figure 1.14.

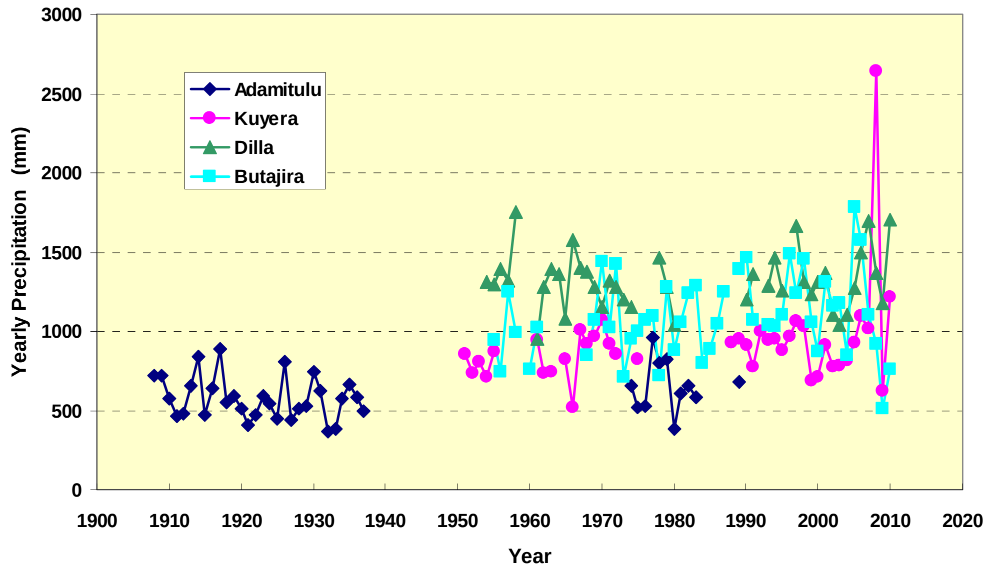


Figure 1.13: Relation between the Data from Admi tul and Dilla Station (1)

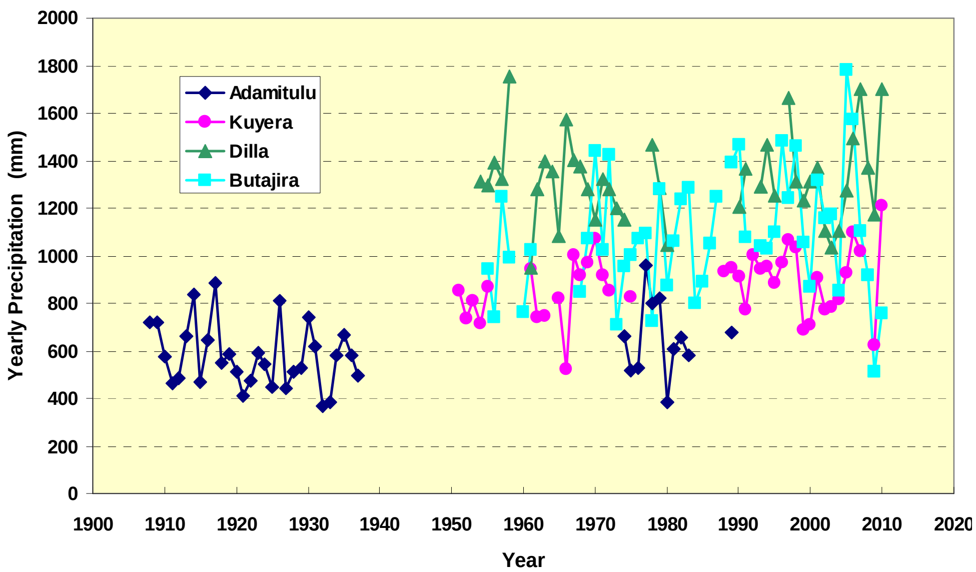


Figure 1.14: Relation between the Data from Admi tul and Dilla Station (2)

The relation between the Adami tuul station and the other 3 stations that have relatively long period of data was found little correlation having the coefficient of correlation between 0.06 to 0.27 based on linear regression method as shown in the following.

- Adamitulu(1908-1989)

  y =0.9442x +567.89; R^2 = 0.0309 (R = 0.18)
- Kuyera (1951-2010)

  y =1.9777x + 813.81; R^2 = 0.073 (R = 0.27)
- Butajira(1955-2010)

  y =3.1552x -5174.3; R^2 = 0.0377 (R = 0.19)
- Dilla(1955-2010)

  y =0.6191x +1301.4; R^2 = 0.0037 (R = 0.06)

On the other hand, the equations all have positive gradient coefficients. As a whole, although no clear trend was recognized, the posibitve coefficient values indicate that the precipitation is slightly on the rise over time.

a.8 Period of precipitation change

1) Selection of data for the analysis

The length of the hydrological cycle changes depending on various conditions. Even at the same observation stations, different parameters have different length of hydrological cycles. Some are long and some are short. It is desirable to use data sets of as long observation period as possible in the analysis of hydrological cycles.

The trend of precipitation change in the four data sets from the stations of long observation period was discussed above. These four sets of data series have a long period but also some periods of missing data. It is not appropriate to complement the data by the auto-correlation method while the relationship between the other surrounding stations can not be used to complement the data as already explained. Thus the missing data can not be complemented properly in any way.

In such circumstances, it is desirable to employ the data sets that have long data period and shorter period of missing data for the analysis.

The data set from Awassa station most satisfies these requirements among the sets of data collected. The observation data has a period of 30 years (1981 − 2010) without any missing data. The variation in annual precipitation is shown in Figure 1.15.

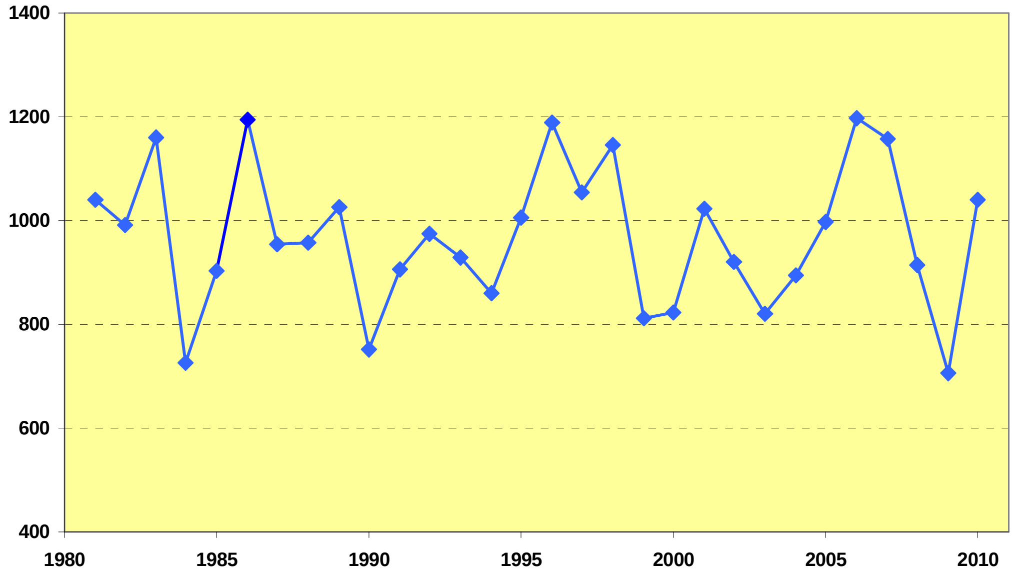


Figure 1.15: Variation in Annual Precipitation at Awassa Station

2) Analysis method of hydrological cycle

There is a standard method for analyzing the characteristics of precipitation cycle, periodical appearance of wet and dry year. The method uses the coefficient of variation (Cv) that is calculated from the ratio between the total precipitation amount from each year, and the average annual precipitation from the all years in the data period. The series of Cv values are analyzed on a graph.

The cycle is delineated using the cumulative value of Cv that is calculated as follows:

$$Cv = \sum (Ki / Kmean - 1)$$

whereas

Ki : Precipitation in year i

Kmean : Average annual precipitation over the entire observation period

In a single hydrological cycle, the cumulative value of coefficient of variation (Cv) becomes 1 or nearly 1.

Result of hydrological cycle analysis

The cumulative curve of Cv is given in Figure 1.16 and the results are also compiled in Table 1.12. As can be seem in the figure, several cycles that are made up of series of wet years and dry years can be recognized in the 30 year precipitation data at Awassa station.

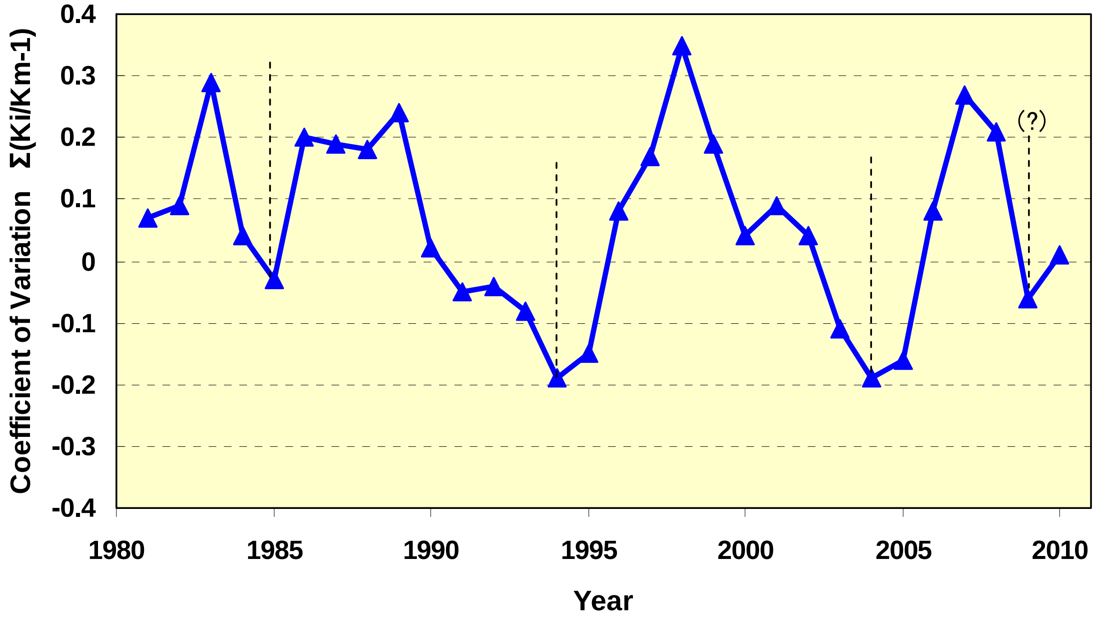


Figure 1.16: Cumulative Curve of Coefficient of Variation in Awassa Station

Table 1.12: Results of analysis for precipitation cycle

Sequence	Duration	Wet Year	Drought Year
1	-1985	- 1983	1984 -1985
2	1986 - 1994	1986 - 1989	1990 - 1994
3	1995 – 2004	1995 - 1998	1999 - 2004
4	2005 - 2009	2005 - 2007	2008 - 2009
5(?)	2010 -	2010 -	--

As show in Table 1.12, the analyzed 30-year data (1981-2010) includes 5 cycles of precipitation. However, the last cycle in the graph (2005 to 2009) starts with three consecutive wet years and ends with two consecutive dry years. The following year is 2010 and that year has relatively more rain than average years. Thus this may be the beginning of the next hydrologic cycle but can also be regarded as a small peak within the previous cycle as that of year 2011 unless the data is followed by several more wet years.

To sum up, the analysis revealed that there are three complete cycles and five incomplete ones (because the data are truncated on either side). The period of the three complete cycles ranges from 5 to 10 years.

a.9 Probability of precipitation changes

Since the amount of precipitation changes every year, the amount of water resources that are formed by precipitation also changes from year to year. Thus, it is necessary to analyze the probability of changes in precipitation amount in addition to the analysis of its tendency in change and cyclic characteristics. One of the objectives of this study is to draw up a water supply plan in the study area. Small amount of rain usually brings about smaller surface water amount and lowered groundwater table in that year. Thus, from the point of view of securing water supply, it is important to analyze the probability of occurrence of dry years.

Out of many methods employed to conduct probability analysis of precipitation, the following four are relatively well known and used: Normal distribution method, Log-normal distribution method, graph method, Log-Pearson III method.

The characteristics of the four methods below employed to analyze the precipitation data to find accidence probability in this study are explained in the following.

1) Normal distribution method : It is based on the assumption that the distribution of precipitation amount follows normal distribution and it is the most basic method in hydrological analysis.
2) Log-normal distribution method : The method was developed to correct deviation of actual rainfall data from normal distribution. The basic principle is the same as the Normal distribution method.
3) Graph method : The use of this method depends on the amount of data available for analysis. With sufficient amount of data for analysis, it is most simple and intuitive, and thus commonly used.
4) Log-Pearson III method : This is the standard method for hydrological analysis for governmental agencies to employ in the USA. The process is a little complicated but introduction of the parameter "skewness", the problem of deviation from normal distribution is sufficiently compensated.

The data from Awassa station was used for the probability analysis as it was employed for the analysis of cycles. An example from Log-Peason III method is given in Figure 1.17. As a result of the analysis, the expected rainfall for different return periods was found to be as summarized in Table 1.13. The result suggests that not much variation in precipitation is likely to occur.

Table 1.13: Results of Precipitation Probability Analysis

	Non-Ex.(%)	Normal1)	Log_Nor2)	P.P3)	Log_PIII4)	Mean5)	RPIY6)
Dry Year	1	646.0	682.6	--	661.2	663.3	100
	2	683.8	710.3	706.3	694.2	698.7	50
	4	725.9	742.5	718.4	731.8	729.7	25
	10	791.0	795.2	781.2	792.0	789.8	10
	25	852.1	848.0	902.0	871.8	868.5	5
	50	968.9	959.1	975.3	966.1	967.3	2
Wet Year	75	1085.7	1084.6	1038.8	1063.5	1068.2	5
	90	1146.7	1156.7	1175.5	1150.5	1157.3	10
	96	1211.8	1238.8	1191.8	1219.5	1215.5	25
	98	1253.9	1294.9	1197.0	1264.2	1252.5	50
	99	1291.7	1347.6	--	1304.4	1314.6	100

Non-Ex : Non exceedence probability.
Normal : Normal Distribution
Log_Nor. : Log-normal Distribution
P.P. : Plotting Position (Hazen Method)
Log_PIII : log-Pearson Type III distribution
Mean : Average of the result obtained from the above 4 methods
RPIY : Return period in years

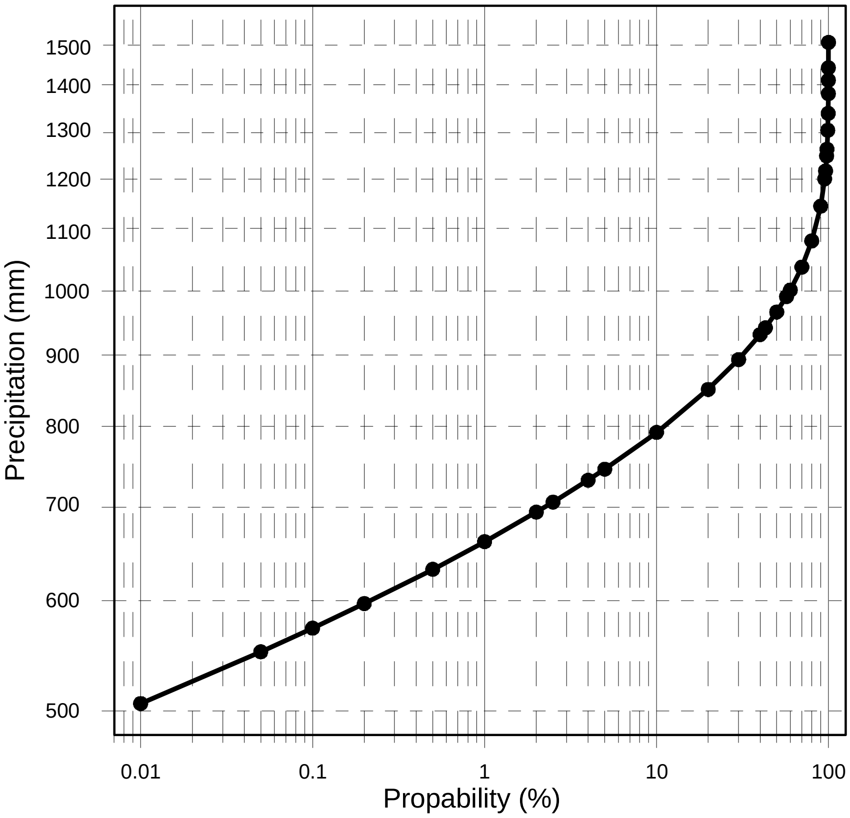


Figure 1.17: Result of Probability Analysis by Log-Pearson III

b. Analysis of other hydrological factors

b.1 Temperature

The influence of temperature is not as great as that of precipitation from the viewpoint of water resources management. However, still temperature affects evaporation amount and thus, it is important to analyze its tendency of change.

Out of all the stations from which meteorological data was collected, 52 stations have temperature data. The data was checked and corrected before use as in the following examples.

- Arata station
  The data for 2009/9/12 is given as 297°C, the data for the preceding and following days are 28.3 and 28.6 °C respectively. Thus, the data was corrected to 29.7.
- Dawaro station
  The data for 2008/7/19 is given as 289 °C, the data for the preceding and following days are both 27.5 °C. Thus, the data was corrected to 28.9.
- Dawaro station
  2007/9/4 is given as 634.5 °C, but there was not information available to correct the data. Thus, the data was discarded.

The basic characteristics of the change in temperature at each station were analyzed using the corrected data and presented in Table 1.14.

Table 1.14: Summarizing of Temperature's Basic Characteristics

Unit: °C

Station	Duration	Average	Max	Min
Aje	1978-2009	19.1	39.5	1.0
Alaba kulito	1989-2010	19.7	36.7	1.0
Alem Tena	1996-2010	20.0	36.0	-1.0
Aleweya	2007-2010	21.6	38.5	3.5
Amarokele	1983-2010	21.5	37.0	6.0
Angacha	1988-2010	19.1	28.7	10.0
Arata	1996-2010	20.2	36.6	0.0
Arbaminch	1987-2010	23.9	38.0	8.0
Arbegona	1995-2008	14.2	23.9	3.4
Arsinegele	1987-2020	18.6	36.1	3.4
Assela	1996-2010	17.8	33.8	1.6
Awassa	1981-2010	19.9	34.2	0.8
Beleala	2008-2010	21.3	33.0	10.8
Beto	1990-2009	27.1	39.5	7.2
Billate	1988-2010	23.1	38.0	3.5
Bodity	1981-2010	18.3	32.5	1.1
Borerda	2008-1010	18.0	33.1	9.0
Buie	2004-2010	18.5	36.3	1.5
Burji	1976-2010	25.4	40.0	1.1
Butajira	1972-2010	18.5	32.9	0.3
Dawaro	2007-2010	20.2	34.5	4.5
Degaga	1969-2010	16.7	33.0	0.5
Dilla	1988-2010	20.4	39.6	3.2
Doyogena	2009-2010	16.5	30.0	2.1
Gato	1975-2010	24.2	39.9	10.0
Geresse	1985-2010	16.3	32.3	0.4
Hageremariam	1987-2010	18.2	32.0	1.0
Hagereselam	1965-2010	13.0	26.2	0.1
Hossana	1981-2010	16.8	32.0	-0.5
Hsenusman	2009-2010	19.6	32.0	6.5
Huruta	1996-2010	17.8	34.4	-3.0
Jinka	1981-2010	21.7	36.3	9.5
Kawakoto_Alicho	2007-2010	12.3	27.0	2.0
Keyafer	1985-2010	22.5	34.8	1.0
Konso	2004-2010	22.5	34.7	10.0
Kulumsa	1996-2010	17.1	30.0	0.5
Kuyera	1961-1972	17.4	35.0	1.0
Langano	1981-2010	21.4	38.0	6.5
Lemen	2009-2010	19.5	32.3	5.5
Mirababaya	1982-2010	24.0	39.6	0.0
Mojo	1996-2010	19.6	35.8	1.0
Ogolcho	1994-2010	20.5	38.0	0.0

Station	Duration	Average	Max	Min
Sankura	2006-2010	20.0	34.0	0.3
Teltele	1975-2010	22.6	37.6	10.0
Wajifo	1979-2010	22.8	38.3	5.3
Werabe	2006-2010	18.7	30.7	1.2
Weteraressa	2004-2010	13.4	28.2	5.0
Wolaitasodo	1981-2010	19.7	33.3	1.0
Wulberg	1978-2010	18.4	34.8	0.4
Yabelo	2004-2010	20.1	32.9	5.4
Yirgachefe	1986-2010	18.1	35.0	-0.2
Zeway	1981-2010	20.6	34.0	2.4
Average	--	19.6	34.4	3.2
Maximum		27.1	40.0	10.8
Minimum		12.3	23.9	-3.0

As can be seen in Table 1.14, the average annual temperature for all the 52 stations used for the analysis is 19.6 ^{o}C, and the maximum and minimum values are 27.1 ^{o}C and 12.3 ^{o}C respectively. The range of change in annual average temperature at all the station is from -3 ^{o}C to 40 ^{o}C.

The annual trend of change in average temperature over the 52 stations is illustrated in the following Figure 1.18.

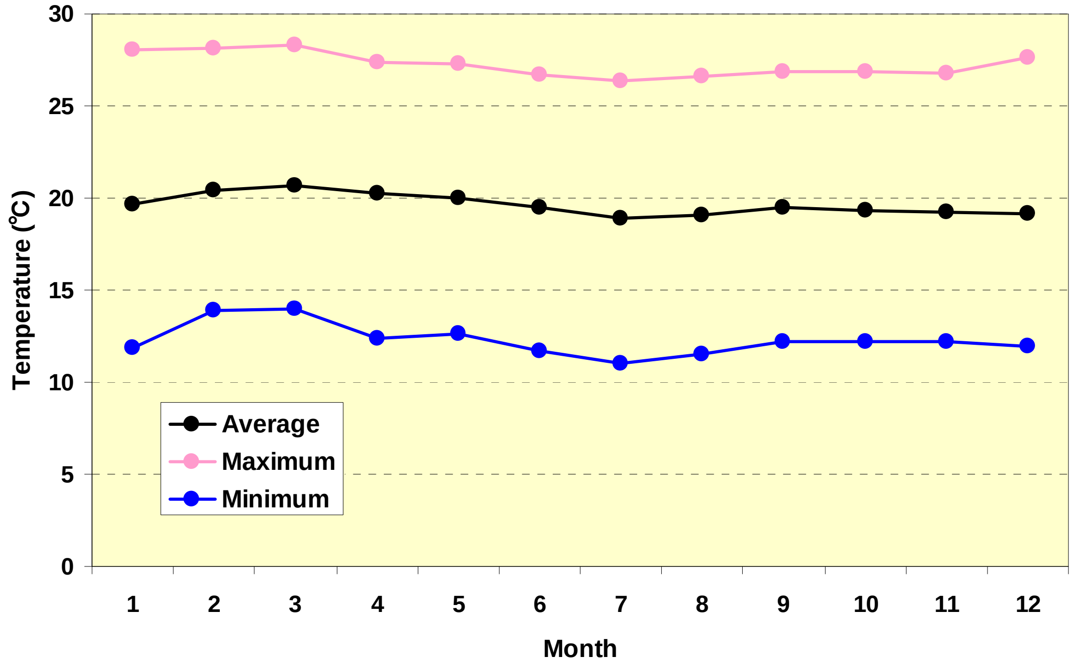


Figure 1.18: Monthly Average Temperature Fluctuation of the 52 Stations.

The variation in average monthly temperature from the 52 stations in the figure shows that the temperature throughout a year has only a slight change of around 20 ^{o}C.

In the case of Hagre selam station that has longest data period, its annual variation is illustrated in Figure 1.19. Within its 46 years of record, the monthly average temperature changes within 2 °C on both upper and lower sides around 18.2 °C. The temperature is higher in the dry season (November to March) and lower in the wet season.

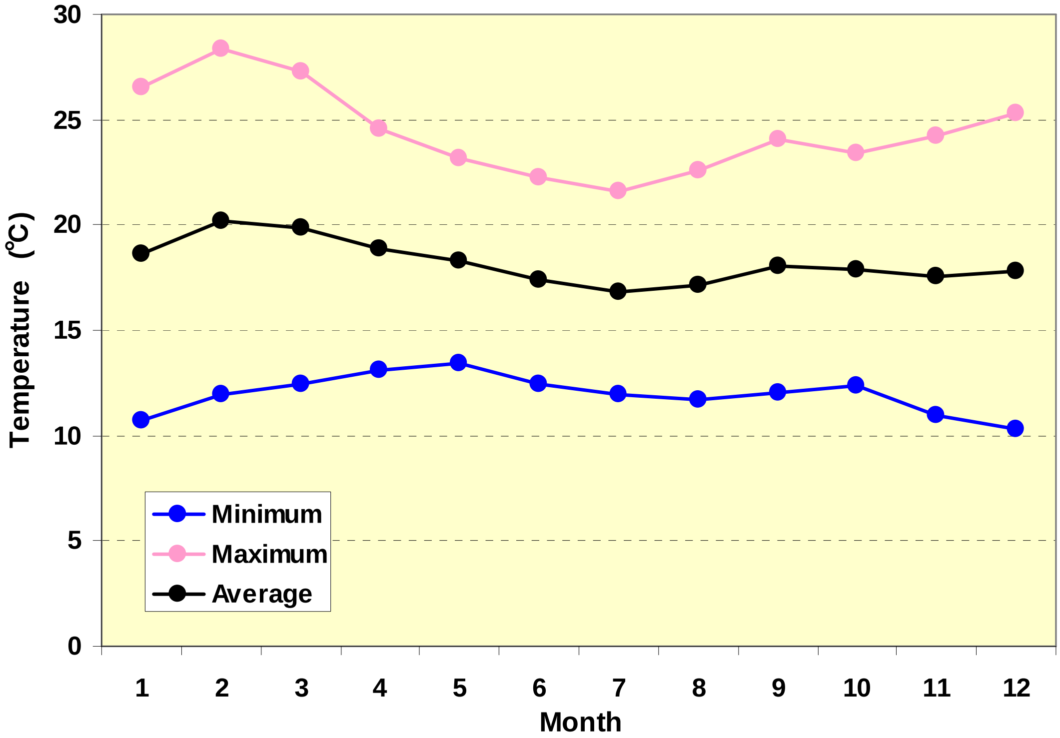


Figure 1.19: Monthly Average Temperature Fluctuation at Station Hagereselam.

b.2 Evaporation

1) Available data

There only a very small number of stations that have data for evaporation as compared with those having precipitation data. Only five stations have evaporation data in the rift valley lakes basin area. The locations of these five stations are shown in Figure 1.20 and the condition of the data availability from the five stations is presented in Table 1.15.

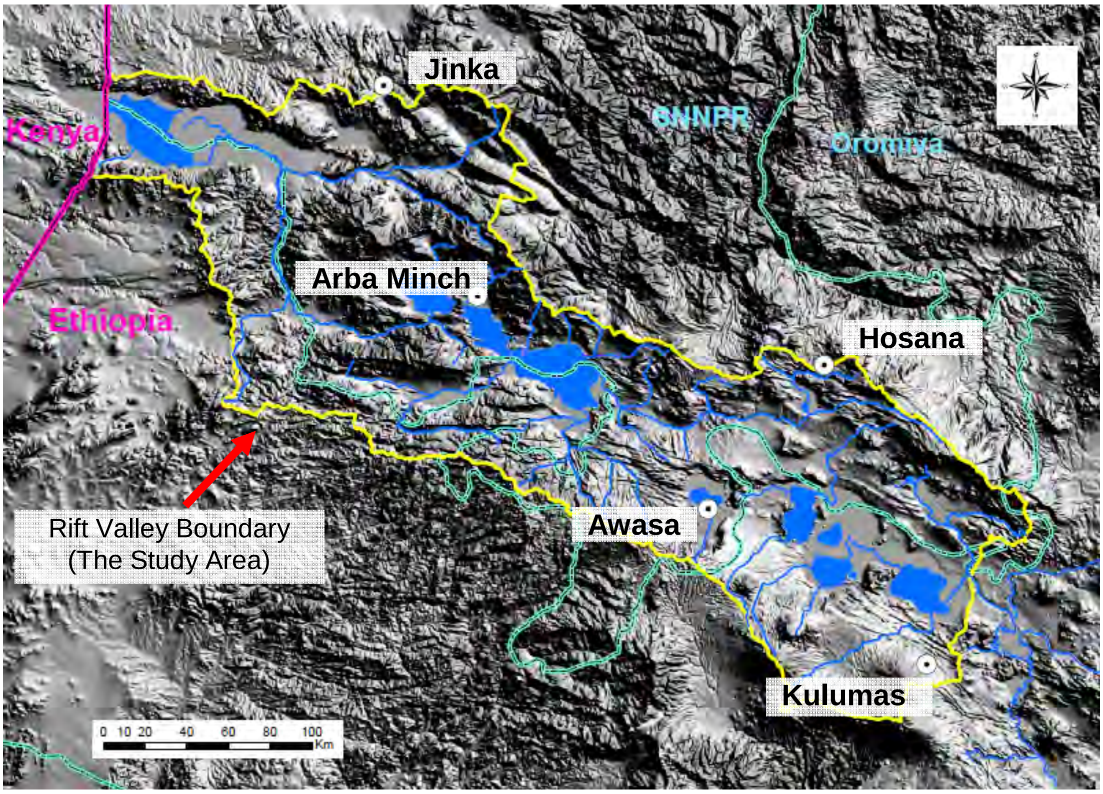


Figure 1.20: Locations of Stations with Evaporation Data for Analysis

Table 1.15: Available Evaporation Data in Rift Valley Area

Station	Duration	Missing Data	Ratio of MD
Arba_Minch	2006 - 2010	617	42.2%
Awassa	1986 - 2010	1,032	11.3%
Hossana	2004 - 2010	1,414	55.3%
Jinka	1989 - 2009	1,605	20.9%
Kulumsa	2008 - 2010	33	3.0%

2) Verification and complementation of missing data

As in the precipitation data, the evaporation data have some errors. Prior to data analysis, maximum effort was made to check for the errors and the errors were corrected as much as possible as in the following examples.

Jinka Station The data for 2001/05/23 is given as 6.50.mm. The last decimal point is an obvious input error. Thus, it was removed and the value was taken as 6.5mm.

Awassa Station The data for 2004/09/21 is given as 2.6.2mm. Either of the two decimal points had to be removed. In this case, the evaporation values for the preceding and following days are 2.87 and 3.0mm respectively. Thus, the value was corrected to be 2.62 mm.

Kulumsa Station The data for 2008/11/25 12:00 is given as 40 mm. The duration of observation for this data is from 9:00 to 12:00 (3 hours). It is normally impossible to get 40 mm evaporation within a few hours. In this case, the evaporation values for the preceding and following days are 0.26 and 0.52 mm respectively. Thus, the value was corrected to be 0.4 mm.

The evaporation data as compared with the precipitation data, has extremely fewer observation stations and also many days with missing data within a limited number of data years. These problems significantly lower the reliability of the available data.

Therefore, the missing data was complemented using the auto-correlation method rather than discarding the important sets of the data periods.

3) Monthly variation of evaporation

With the complemented data sets, the monthly average evaporation values and their annual sum for the five stations were calculated and presented in Table 1.16.

Table 1.16: Monthly and Annual Average of Evaporation in Rift Valley Area

Month	A_Minch	Awassa	Hossana	Jinka	Kulumsa	Average
Jan	188.4	191.4	130.9	137.5	234.1	176.5
Feb	173.1	193.3	147.1	137.9	213.9	173.1
Mar	219.2	193.4	186.5	139.7	282.8	204.3
Apr	147.3	161.7	148.2	116.7	212.2	157.2
May	129.1	165.2	118.9	104.3	364.7	176.4
Jun	146.9	152.1	111.4	95.3	222.8	145.7
Jul	126.4	132.1	105.3	96.1	191.7	130.3
Aug	146.6	137.1	89.3	104.0	146.3	124.7
Sep	135.7	131.7	106.6	121.0	171.6	133.3
Oct	143.1	151.6	135.2	112.3	348.2	178.1
Nov	154.8	174.5	166.3	111.6	285.5	178.5
Dec	136.6	179.2	145.6	118.1	314.4	178.8
Min	126.4	131.7	89.3	95.3	146.3	124.7
Max	219.2	193.4	186.5	139.7	364.7	204.3
Avg	153.9	163.6	132.6	116.2	249.0	163.1
Total	1847.2	1963.3	1591.3	1394.5	2988.1	1956.9

The monthly average, maximum and minimum values of evaporation over the five stations presented in the table above are also illustrated in Figure 1.21.

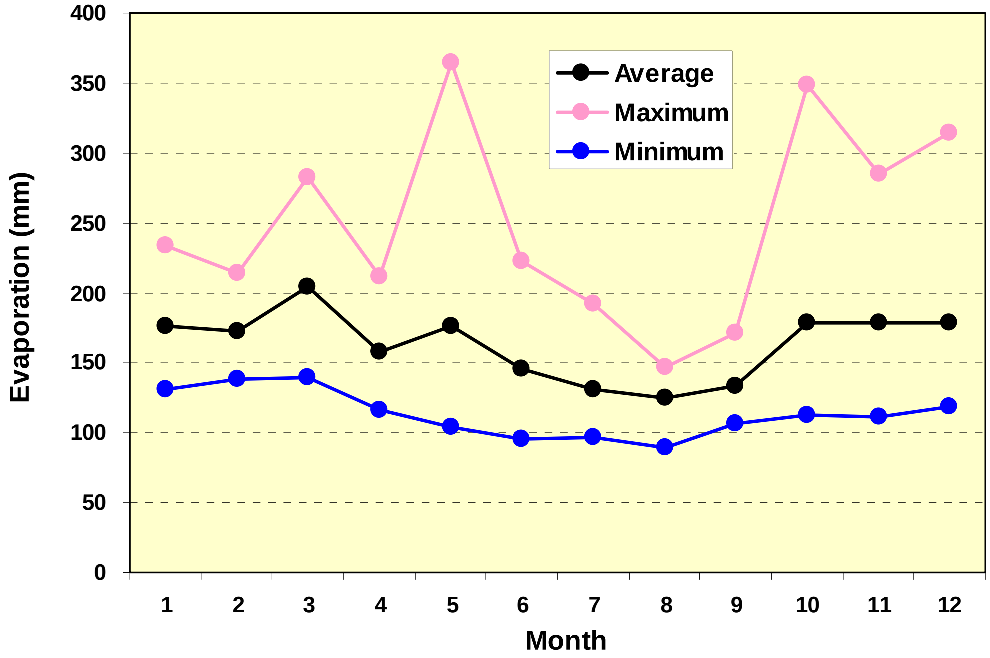


Figure 1.21: Monthly Average Evaporation Fluctuation of the 5 Stations.

The values of monthly average, and maximum and minimum are all based on the monthly average of all the five stations. However, the maximum values were all taken from Kulumsaa station. As can be seen in Table 1.16, if the data from Kulmsaa station is ignored, the values from the other four stations are relatively close to each other with their range between 1395mm and 1963mm. The difference in evaporation is as much as 600mm and the ratio between the maximum and minimum values are 71%. On the other hand, the maximum value of Kulmsaa station is 1000 mm more than the largest value (Awassa station) of the other four stations. As for the minimum value, it is more than a double of the smallest value from the four (Jinka station).

The amount of evaporation is affected by many factors but most of these factors are also controlled by the position on the globe and topography of the area. Therefore, the four stations and Kulumsa station that are all in the same rift valley lakes basin having relatively similar position and topographical conditions should not have such large difference in evaporation.

On the other hand, as discussed earlier, abundance of missing data in the data series in comparison with precipitation data, may have affected the accuracy of the analysis. However, the data from Kulmusa station has the least missing data of all in both its ratio and actual amount. Thus the analysis result from this station is considered relatively reliable.

The essence of the problem may lie in the fact that Kulumsa station only has three years of data, covering the year 2008 to 2010, which is the shortest among the five stations. The result of the analysis of hydrological cycles indicates that two out of the three years dry years (2008 and 2009) and the last one year is a wet year (2010). In dry years, usually the amount of evaporation increases while the precipitation is decreased. This can be one of the reasons that Kulmusaa station has larger evaporation values than the other stations.

4) Relation between evaporation and altitude

As explained earlier, evaporation is affected by the position on the globe and the topography of the area. Since the positions of the five stations are nearly the same on a global scale, an analysis was conducted to assess the effect of topography on the evaporation among the four stations. The pan evaporation data plotted in Figure 1.22 from the five stations shows, however, no clear relation between the amount of evaporation and the elevation of the stations.

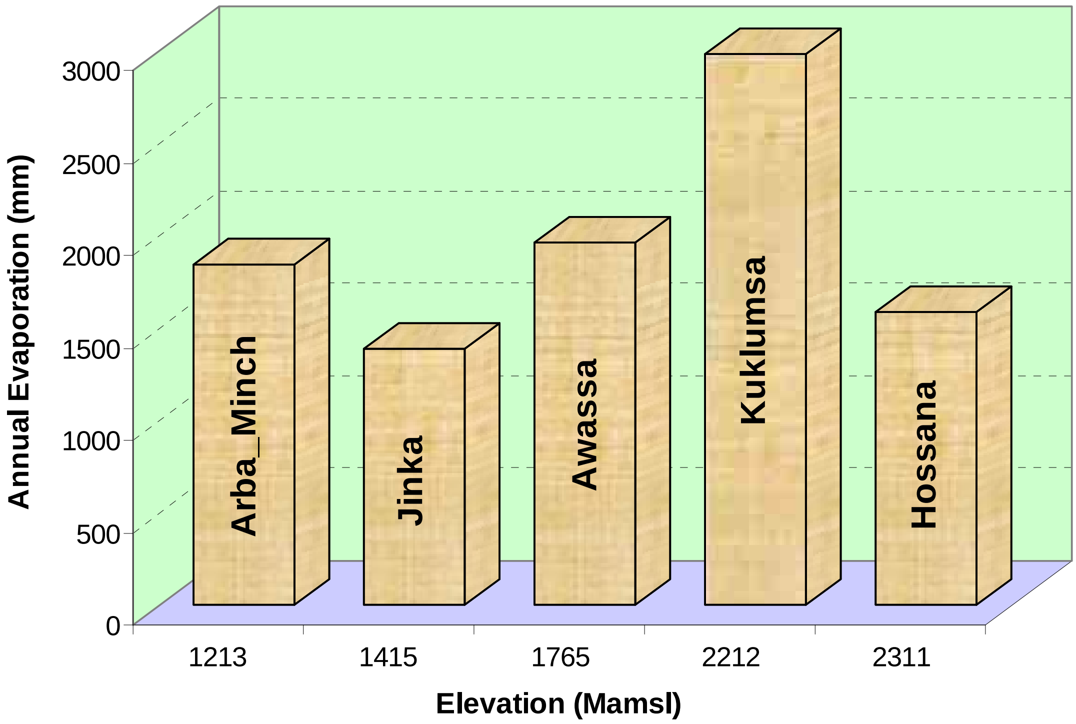


Figure 1.22: Relation between Annual Evaporation and Elevation of the Stations

1.3.2 Analysis of hydrological data

a. Distribution of lakes and their roles

a.1 Distribution of lakes

The rift valley area, as can be known from its name, is a valley area. There are chains of mountains on both sides of the valley that extends in NE-SW directions in the central part of the area. There are eight major lakes in the area and many rivers originate from the mountain areas on the border of the valley and flow into these lakes. The locations of the major lakes and rivers are shown in Figure 1.23.

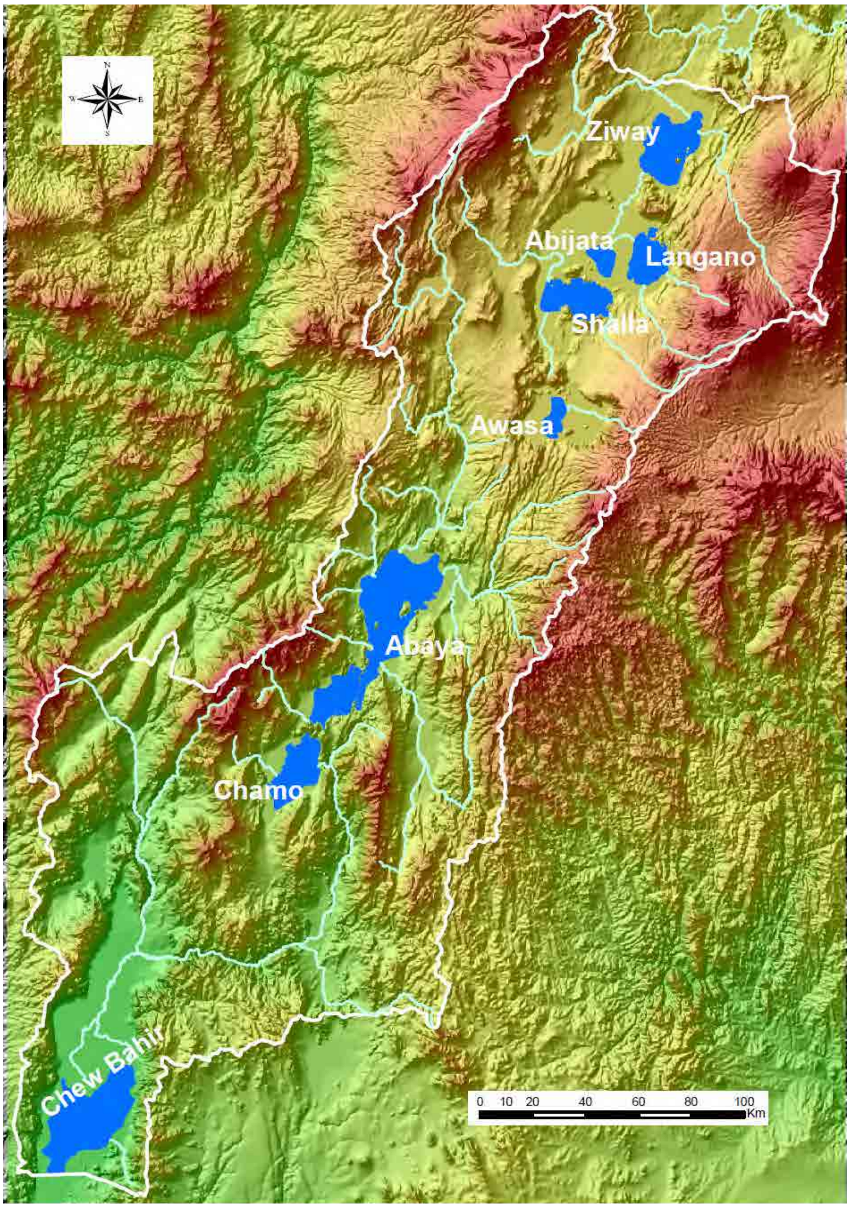


Figure 1.23: Major Lakes and Rivers in Rift Valley Area

The basic characteristics of the lakes are compiled in Table 1.17 in the order of their locations from north to south.

Table 1.17: Major Lakes in Rift Valley Area

Name	Area(km^2)	Ele_(Mamsl)
Ziway	422.9	1,641
Langano	233.0	1,583
Abijata	87.3	1,579
Shalla	309.8	1,559
Awasa	93.5	1,687
Abaya	1,094.8	1,180
Chamo	315.3	1,110
Chew Bahir	762.8	498

Ele: Elevation

a.2 Evaporation from the lakes

There is no inflow of surface water into the rift valley basin area from the other surrounding basins. The water resources formed by precipitation are simply consumed by evapotranspiration and use by human activities. The result of hydrological analysis of Lake Abalya basin conducted under the groundwater modeling 1 indicate that evaporation from the lake surface accounts for about 95% of the annual average evaporation amount from the entire basin (1062.2 Mm^3 /1117.8 Mm^3 = 95%). In other lake basins in the study area, this ratio varies depending on many conditions such as river network distribution, irrigation system and its area, population, and level of economic activities. However, in consideration of similarity in these conditions within the rift valley area, the amount of water resources consumption in the study area is assumed to be nearly universal and close to that of Lake Abaya basin. Namely, around 95% of evaporation occurs from the lake surface.

In order to estimate the consumption amount of water resources within the study area, the data of lake areas and the corresponding evaporation values obtained as a result of the evaporation analysis. Since no clear relation is recognized between the evaporation amount and their topography of the observation stations, the Thiessen method was employed to determine the evaporation value assigned to each lake basin. Figure 1.24 illustrates the result of the Thiessen division of the study area based on the evaporation stations.

The average annual total evaporation amount from all the lakes in the study area is calculated by the following formula:

$$\mathbf{Evapo} = \Sigma(\mathbf{Evapo_i} \times \mathbf{L_{areai}})$$

whereas
Evapo: Total annual evaporation from the lakes in the study area
$Evapo_i$: Annual evaporation amount from area “i” based on Thiessen division
L_{areai}: Area of the lake corresponding to $Evapo_i$.

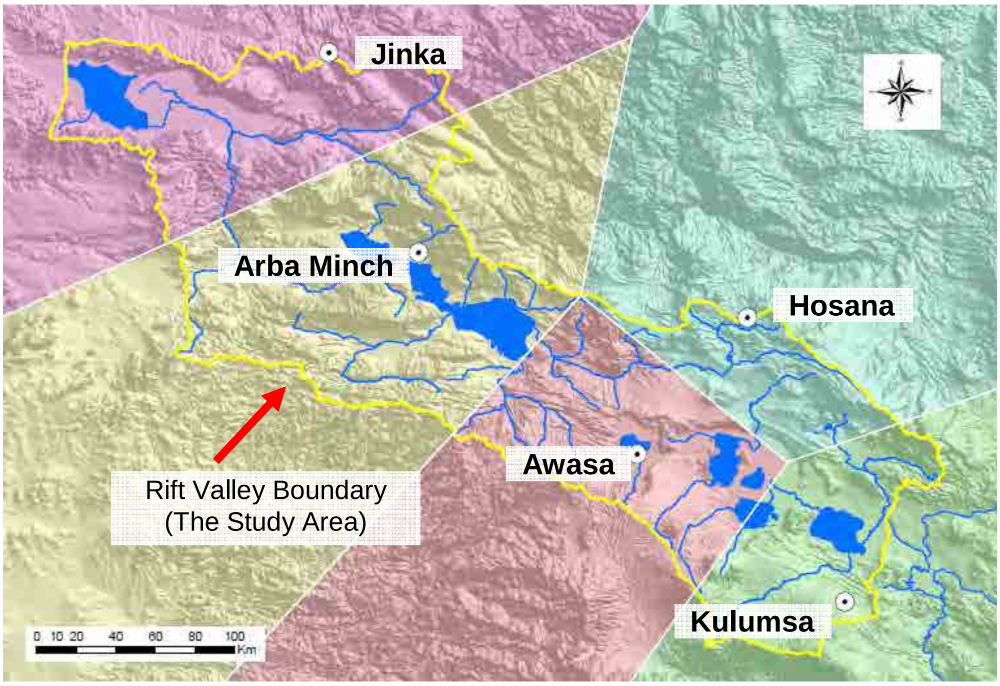


Figure 1.24: Theissen Division for Average Annual Evaporation

The amount of evaporation from the major lakes in the rift valley area was calculated as above and presented in Table 1.18.

Table 1.18: Average Annual Evaporation from Lakes in Rift Valley Area

Name	Area_Km^2	M_Station	Pan_(mm)	Evapo (Mm^3)
Ziway	422.9	Kulumsa	2988	1,263.6
Langano	139.2	Kulumsa	2988	415.9
Langano	94.2	Awassa	1963	185.0
Abijata	87.3	Awassa	1963	171.4
Shalla	309.8	Awassa	1963	608.1
Awassa	93.5	Awassa	1963	183.5
Abaya	1,086.6	Arba_Minch	1847	2,007.0
Abaya	8.2	Awassa	1963	16.1
Chamo	315.3	Arba_Minch	1847	582.4
Chew Bahir	762.8	Jinka	1395	1,064.1
Others*	27.8	--	--	48.1
Total	**3,347.6**	--	--	**6,545.2**

Others: 13 small lakes in Rift valet with water area from 0.1 to 13.2km^2.
M_Station: Meteorological station
Pan(mm): Annual average evaporation amount.
Evapo(Mm^3): Total evaporation amount in unit of million m^3.

a.3 Inflow into lakes

The evaporation of water from the lakes within the rift valley area accounts for more than 90% of water consumption in the study area. This evaporation amount (from the lake water) is composed of inflow from rivers, inflow from groundwater, and direct precipitation over the lake surface. The direct precipitation over the lake surface plays an important role of replenishing the water in the lakes but is not very significant in terms of use as available water resources. Also its effect should be subtracted in analyzing river flows characteristics and groundwater recharge within the study area. Thus, the effect of direct precipitation over the lake surface was calculated using the same correspondence of stations to lakes discussed earlier under “evaporation from the lakes”. The result is presented in Table 1.19.

Table 1.19: Direct Precipitation Amount over the Lakes in the Rift Valley Area

Name	**Area_Km^2**	**M_Staiton**	**A_Rain(mm)**	**E_Rain(Mm^3)**
Ziway	134.0	Zeway	740	99.2
Ziway	128.3	Adamitulu	597	76.6
Ziway	81.2	Ogolcho	708	57.5
Ziway	55.9	Meki	735	41.1
Ziway	23.5	Erbore	492	11.5
Langano	195.5	Langano	777	151.9
Langano	35.1	Bulbula	665	23.4
Langano	2.4	Degaga	1086	2.6
Abijata	60.6	Langano	777	47.1
Abijata	26.7	Bulbula	665	17.8
Shalla	112.0	Langano	777	87.0
Shalla	106.1	Arsinegele	928	98.5
Shalla	91.7	Aje	2582	236.7
Awassa	75.0	Awassa	969	72.7
Awassa	18.5	Belela	1039	19.2
Abaya	387.9	Wajifo	2061	799.4
Abaya	329.8	Mirababaya	712	234.8
Abaya	193.8	Arbaminch	880	170.6
Abaya	143.1	Chencha	1353	193.6
Abaya	22.4	Humbotebela	1134	25.4
Abaya	17.8	Billate	793	14.1
Abaya	0.1	Dilla	1319	0.1
Chamo	167.1	Arbaminch	880	147.1
Chamo	102.6	Gumaide	928	95.2
Chamo	40.6	Gidole	1163	47.2
Chamo	5.0	Geresse	2139	10.7
Chew Bahir	762.8	Kolme	854	651.4
Others*	27.8	--	--	28.7
Total	**3347.6**	**--**	**--**	**3,461.0**

Others: 13 small lakes in the rift valley with water area from 0.1 to 13.2km^2.

The amount of water flowing into the lakes that are composed of inflows from river and groundwater, in the rift valley area was calculated using the data in Table 1.18 and Table 1.19 as follows:

Inflow into the lakes = 6,545.2 − 3,461.0 = 3084.2 (Mm^3)

b. Water resources amount in the rift valley area

As presented in the result of groundwater modeling (refer to Ch7 of Supporting Report), the evaporation from the lakes accounts for more than 95% of the net water resources amount in the study area. If we assume that the variation in this ratio for different parts of the study area is relatively small enough not to affect the calculation result for the entire study area, the net consumption amount of water resources in the study area can be estimated by the following formula.

Water resources consumption amount for the entire study area = 3,084.2 / 95% = 3,246.5 (Mm^3)

This water resources amount composed of both river flow and groundwater flow in the study area can be used to find per capita water resources amount. If the population data for year 2005 from Halcrow 2008 (8.9Million) is used, it can be calculated as follows:

Per capita water resources amount = 3246.5 / 8.9 = 364.8 m^3

c. Rivers in the rift valley area

The surface water resources in the rift valley area are composed of waters in lakes and ponds and in rivers. The evaporation from the lakes accounts for most of the consumption amount of the water resources in the area. Meanwhile, since the direct precipitation over the lakes is smaller than evaporation from the lakes, the waters in the lakes are maintained by inflow of surface water and groundwater.

Amount of groundwater inflow into the lakes is very small as found out in groundwater modeling of Ch7. Thus, the water levels in the lakes are considered mostly maintained by inflow from rivers.

c.1 Collected river flow data

In order to analyze the characteristics of the river and their flows, daily flow data from 36 stations were collected from the hydrology section of Ministry of Water and Energy. The location of the stations is shown in Figure 1.25 and the basic information of the stations is tabulated in Table 1.20.

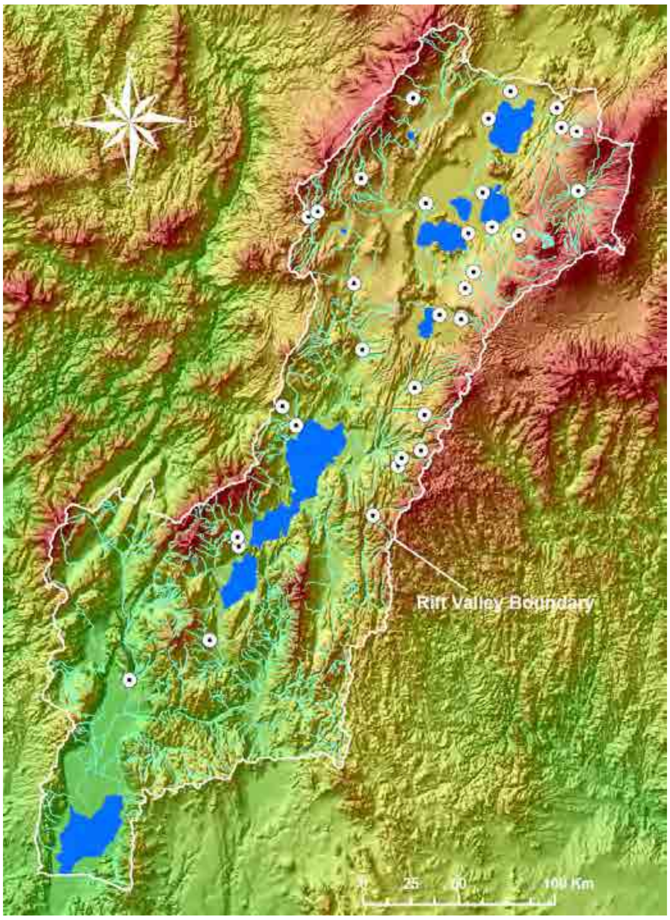


Figure 1.25: Location of River Flow Observation Stations

Table 1.20: Data for 36 River Flow Stations

Stations	Easting	Northing	Duration	MD_1	MD_2
40-Spring	339512	663417	1981 - 2005	3.9%	3.9%
Ashebeka_Sagure	517128	848925	1982 - 2004	51.1%	6.3%
Batena	375846	835187	1987 - 2007	21.3%	21.3%
Bedessa	422585	705263	1982 - 2006	4.2%	4.2%
Bilate_Alaba Kulito	399655	800503	1971 - 2007	2.1%	2.1%
Bilate_Bilate Tena	403995	765960	1970 - 2006	28.0%	8.1%
Chiufa_Arata	507714	882087	1985 - 2007	9.0%	9.0%
Dedeba_Kuyera	461890	806473	1979 - 2006	3.2%	3.2%
Djidu_Childern	437129	842330	1983 - 2008	20.6%	14.0%
Ferfero_Wulbareg	403265	855389	1990 - 2007	13.3%	13.3%
Gato_Gidole	324403	614371	1975 - 1999	22.4%	11.8%
Gedemso_Langano	485656	825708	1995 - 2007	28.6%	28.6%
Gidabo_Aposto	431294	746251	1977 - 2006	3.7%	3.7%
Gidabo_Meass	434731	713366	1997 - 2006	14.0%	14.0%
Guder_Hoseaeina	380597	838001	1988 - 2006	22.8%	18.5%
Hamassa_Humbo	362464	736336	1985 - 2006	8.3%	8.3%
Hamassa_Wajifo	369543	726368	1980 - 2005	11.6%	11.6%
Harekelo_Langano	466914	847828	1980 - 2007	17.0%	14.0%

Stations	Easting	Northing	Duration	MD_1	MD_2
Katar_Abura	505509	892037	1970 - 2008	9.7%	9.7%
Kekersitu_Adamitulu	469823	886464	1980 - 2010	0.0%	0.0%
Kolla_Alete_ Wondo	436429	732022	1980 - 2006	6.1%	6.1%
Kulfo_Arba Minchi	338919	668166	1976 - 2008	14.1%	11.4%
L.Timala_Sagure	516543	848925	1981 - 2007	15.1%	15.1%
Lake_Shalla	459232	826755	2006 - 2010	15.8%	15.8%
Lipiso_L.Langano	471625	829973	1997 - 1999	35.1%	35.1%
Meki_Meki Village	481273	900885	1969 - 2006	13.7%	8.9%
Melka Oda_Oda	457536	797941	1998 - 2006	9.9%	9.9%
Rinzaf_Butagera	430521	897106	1982 - 2009	36.0%	22.0%
Sala_Dilla College	424474	709391	1997 - 2006	9.3%	9.3%
Tikur Woha_Dato Village	444384	784102	1980 - 2006	3.1%	3.1%
U.Gelana_Yirga Cheffie	409602	679526	1981 - 2006	3.3%	3.3%
Weira_Hosaena	380859	838014	1987 - 2007	11.4%	11.4%
Weito_Bridge	282600	593615	1980 - 2007	16.1%	16.1%
Werka_Wondo	455510	781813	1998 - 2006	19.4%	19.4%
Wolkesa_Assela	515752	879935	1994 - 1994	3.3%	3.3%
Wosha_Wondo Genet	455741	783121	1980 - 2006	6.9%	6.9%

Easting & Northing: Coordinate of precipitation observation station in projection Adindan UTM zone 37N.
MD_1: Percentage of missing data for the whole observation years.
MD_2: Percentage of missing data except those years without any observation data.

c.2 Verification of river flow data

Verification of the obtained data and data complementation were conducted prior to data analysis the same way as in precipitation and evaporation data analysis.

The following are some examples of error correction.

Station Kulfo_Arba Minchi: This is the biggest value in the series. On the other hand, the largest value of river flow during high water in the other data series is 81.995 m^3/s. So the value from Kulfo station is more than twice this value. The corresponding probability of occurrence is for this value was calculated to be once in 10,000 years and considered abnormal. The data for the preceding and following days are 23.13 and 26.671m^3/s respectively. In consideration of these values, the data was corrected to be 69.37 m^3/s.

Station Wolkesa_Assela: The flow data for 1994/09/21 is given as 16.264 m^3/s. This is the biggest in the data series. Within a year of observation period for this data series, more than 200days have values that are less than 0.034 and more than 300 days have values less than 0.756. Therefore, this data series is considered to be that of spring discharge but not of river discharge. In addition, the second largest value in the same data series is 3.111 m^3/s, which is less than 1/5 of the largest value. If the probability of high water occurrence was calculated based on the top 50days of high water data in the series, the probability of occurrence of 16.264 m^3/s.of river flow is calculated to be once in 100,000 years. Thus it is considered an error. The data for the preceding and following days are 1.296 and 2.064 m^3/s respectively. Therefore the data was corrected to be 1.626 m^3/s.

Station Gato_Gidole: The flow data for 1981/07/26 is given as 210.4216.264 m^3/s. This is the biggest in the data series. The result of probability analysis using the top 50 flow data of high water for 25 years (1975-1999) indicates that the flow of this magnitude only occurs one in 10,000 years. The data for the preceding and following days are 0.056 and 2.181 respectively. Therefore the data was corrected to be 2.104 m^3/s.

c.3 Complementation of river flow data

Same as in the precipitation data and evaporation data, the collected river flow data contains missing data as well. The ratio of missing data is, as shown in Table 1.20, 0 to 51.1%. If the years with less than one year observation period are ignored, the ratio is calculated to be 0 to 35.1%.

It is desirable in principle to use the relation with the stations in surrounding areas to complement the data of river flow. However, as it was reveled in groundwater modeling 1, even the two observation stations on Bilate River have no correlation between them. This is considered due to the following two reasons.

- The complexity in river flows within the rift valley area
- Problem in accuracy of flow measurement
- Difficulty in river flow estimation: it is well known that river flow data tends to be least accurate among other hydrological parameters due to all the errors and uncertainties involved in creating H-Q rating curves and so forth.

In any case, the data was complemented by the auto-correlation method as in the precipitation analysis because the correlation with the surrounding station can not be used.

c.4 Average river flow rate

The calculated values, based on the complemented data, for average daily flow rate, daily maximum and minimum flow rates for each station are presented in Table 1.21.

Table 1.21: Daily Average, Maximum, and Minimum Flow Rates

Unit:m^3/sec

Station	Average	Max	Max_day	Min	Min_day
40-Spring	0.152	0.333	2005/1/26	0.058	--
Werka_Wondo	0.259	0.785	2001/9/7	0.000	--
Wolkesa_Assela	0.322	3.111	1994/7/24	0.001	--
Melka Oda_Oda	0.329	8.942	1998/5/3	0.000	--
Hamassa_Humbo	0.620	25.706	1989/10/18	0.000	--
Wosha_Wondo Genet	0.637	7.843	1985/9/17	0.105	1980/11/14
Gato_Gidole	0.643	164.83	1981/5/9	0.000	--
Rinzaf_Butagera	0.743	43.295	1996/3/18	0.000	--
L.Timala_Sagure	0.914	51.695	2006/8/16	0.000	--
Dedeba_Kuyera	1.078	14.82	--	0.007	1984/3/14
Batena	1.205	24.83	1988/8/19	0.000	--

Station	Average	Max	Max_day	Min	Min_day
Guder_Hoseaeina	1.218	52.239	1997/10/26	0.000	--
Harekelo_Langano	1.349	13.519	--	0.000	--
Lipiso_L.Langano	1.496	9.3	1999/7/19	0.110	--
Ashebeka_Sagure	1.560	65.268	1983/8/17	0.320	--
Hamassa_Wajifo	1.614	32.388	--	0.000	--
Chiufa_Arata	1.809	13.774	1994/7/24	0.000	--
Lake_Shalla	1.927	2.56	--	1.340	--
Bedessa	1.936	48.434	1988/7/25	0.000	--
Gedemso_Langano	2.041	53.365	1997/8/6	0.002	2004/1/15
Ferfero_Wulbareg	2.230	104.366	--	0.000	--
Tikur Woha_Dato Village	2.722	6.725	2005/10/29	0.000	--
Kolla_Alete_ Wondo	2.833	42.308	2005/9/23	0.000	--
Sala_Dilla College	4.102	44.613	1997/11/24	0.203	2005/4/5
U_Gelana_Yirga_Cheffie	4.247	69.611	2001/9/26	0.000	--
Kekersitu_Adamitulu	5.506	50.8	1983/10/20	0.000	--
Djidu_Childern	5.846	180.66	1996/8/7	0.000	--
Gidabo_Aposto	6.524	92.452	2006/8/16	0.000	--
Weira_Hosaena	7.399	239.475	1999/10/4	0.313	--
Meki_Meki Village	8.596	139.618	1998/8/15	0.000	--
Kulfo_Arba Minchi	9.271	81.955	2001/7/9	0.000	--
Bilate_Kulito	12.032	118.775	2007/5/15	0.036	--
Katar_Abura	12.862	262.049	1977/10/29	0.001	--
Gidabo_Meass	16.286	50.546	1997/8/9	0.152	2002/8/4
Bilate_Tena	17.562	283.54	1986/7/29	0.000	--
Weito_Bridge	72.170	854.186	1997/11/27	0.000	--

Max_day: the day of maximum river flow
Min_day: the day of minimum river flow
-- : more than 1 day corresponding to the maximum or minimum river flow.

The results indicate that there is a large variation in daily average flow rates among the stations: minimum of 0.152 m^3/sec to maximum of 72.170 m^3/sec, with 500 times difference. Generally the difference in flow rates is explained by the size of the basin and the amount of precipitation over the basin. However, it has be pointed out that some of the data series, as will be explained in detail in the following section, are of spring flows not river flows as they are very small and constant throughout a year.

c.5 Seasonal variation in river flow rates

In the rift valley area, there is a clear distinction between the wet and dry seasons in terms of precipitation. On the other hand, river flow is formed by direct runoff from precipitation and recharge from groundwater (base flow). The base flow component generally has small seasonal variation and thus, the level of variation in river flow is determined by the precipitation. The monthly average river flow rates for the 36 stations are compiled in Table 1.22.

Table 1.22: Monthly Average River Flow Data for 36 Stations

Unit:m^3/sec

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40-Spring	0.15	0.15	0.15	0.14	0.14	0.15	0.15	0.15	0.16	0.16	0.17	0.17
Ashebeka_Sagure	0.61	0.67	0.79	1.17	0.98	0.93	2.52	6.12	2.34	1.14	0.67	0.66
Batena	0.33	0.44	0.44	0.86	0.94	1.08	1.72	3.29	2.77	1.72	0.55	0.27
Bedessa	0.58	0.36	0.36	1.03	2.78	2.79	1.92	2.18	3.45	4.51	2.27	0.93
Bilate_Kulito	1.58	2.07	3.2	7.2	8.8	10.0	16.4	29.6	33.8	20.6	7.5	3.0
Bilate_Tena	2.86	3.67	6.80	11.0	13.6	16.5	23.9	37.4	46.3	31.7	13.2	3.1
Chiufa_Arata	0.26	0.31	0.57	1.01	0.99	1.09	3.39	5.85	5.04	2.18	0.57	0.32
Dedeba_Kuyera	0.11	0.12	0.24	0.67	0.76	0.62	1.07	2.70	3.62	2.35	0.46	0.16
Djidu_Childern	0.47	1.69	4.18	8.08	9.05	6.96	9.22	13.38	10.29	5.32	0.63	0.62
Ferfero_Wulbareg	0.60	0.44	0.64	2.07	1.96	2.45	4.88	6.59	3.69	2.24	0.59	0.46
Gato_Gidole	0.40	0.58	0.81	0.78	1.33	0.45	0.46	0.37	0.34	0.65	0.82	0.45
Gedemso_Langano	0.25	0.15	0.30	0.79	0.92	1.19	4.29	7.26	4.96	3.05	0.84	0.34
Gidabo_Aposto	2.21	2.07	2.54	5.15	8.48	7.20	6.84	10.0	11.7	13.1	5.57	3.10
Gidabo_Meass	7.30	4.87	4.52	11.21	21.82	17.7	17.1	21.6	23.5	31.6	20.2	13.1
Guder_Hoseaeina	0.07	0.15	0.23	0.57	0.83	0.84	1.87	3.94	3.28	2.30	0.34	0.10
Hamassa_Humbo	0.11	0.11	0.10	0.28	0.73	0.69	1.21	1.72	1.04	0.74	0.48	0.20
Hamassa_Wajifo	0.36	0.30	0.63	1.87	2.47	2.11	2.85	3.59	2.12	1.72	0.85	0.39
Harekelo_Langano	0.98	0.69	0.42	0.29	0.26	0.33	0.50	1.52	3.02	3.89	2.65	1.61
Katar_Abura	2.26	2.62	3.54	5.89	5.54	5.99	18.61	53.05	34.43	14.62	4.41	2.47
Kekersitu_ Adamitulu	4.44	2.80	1.66	1.29	1.10	1.11	1.76	5.46	12.80	14.58	11.59	7.39
Kolla_Alete_ Wondo	0.68	0.56	0.59	1.31	2.61	3.12	3.49	5.30	5.26	6.12	3.09	1.72
Kulfo_Arba Minchi	4.80	4.56	4.82	9.47	13.2	10.0	11.1	11.3	10.8	14.9	10.1	5.89
L.Timala_Sagure	0.19	0.22	0.26	0.50	0.44	0.40	1.39	4.74	1.55	0.68	0.29	0.21
Lake_Shalla	1.87	1.83	1.76	1.68	1.71	1.74	1.85	2.04	2.21	2.26	2.15	2.02
Lipiso_L.Langano	0.31	0.26	0.40	0.38	1.43	0.58	2.30	4.31	3.31	3.05	1.06	0.42
Meki_Meki Village	0.94	1.81	4.53	6.37	5.87	5.38	18.3	29.0	19.1	7.86	2.55	0.76
Melka Oda_Oda	0.04	0.03	0.12	0.41	0.59	0.21	0.20	0.24	0.63	1.21	0.18	0.05
Rinzaf_Butagera	0.15	0.24	0.96	0.93	0.88	0.53	1.42	1.91	1.22	0.49	0.09	0.04
Sala_Dilla College	1.61	0.87	0.87	2.20	6.46	4.82	3.50	5.40	5.44	9.95	5.79	2.09
Tikur Woha_Dato Village	2.20	1.90	1.80	1.86	2.38	2.88	2.94	3.25	3.66	3.89	3.19	2.68
U_Gelana_ Yirga_Cheffie	1.31	0.95	0.91	2.99	9.74	6.11	3.21	3.01	5.10	10.3	5.09	2.06
Weira_Hosaena	0.86	1.15	2.39	6.60	6.66	5.97	12.9	23.2	16.3	9.43	1.88	0.90
Weito_Bridge	41.90	30.9	41.1	79.7	128.2	75.3	77.8	77.4	70.0	103.8	82.3	54.6
Werka_Wondo	0.25	0.24	0.25	0.27	0.26	0.25	0.23	0.26	0.30	0.32	0.26	0.25
Wolkesa_Assela	0.02	0.02	0.10	0.07	0.03	0.05	1.02	1.04	0.95	0.03	0.01	0.00
Wosha_Wondo Genet	0.48	0.51	0.53	0.61	0.67	0.64	0.66	0.74	0.85	0.86	0.58	0.51

A graph showing the variation in monthly flow rates was prepared based on the data in Table 1.22 in order to visualize the pattern in seasonal fluctuation. As a result, the following four patterns of flow rates variation were recognized from the data.

c.5.1 Pattern 1

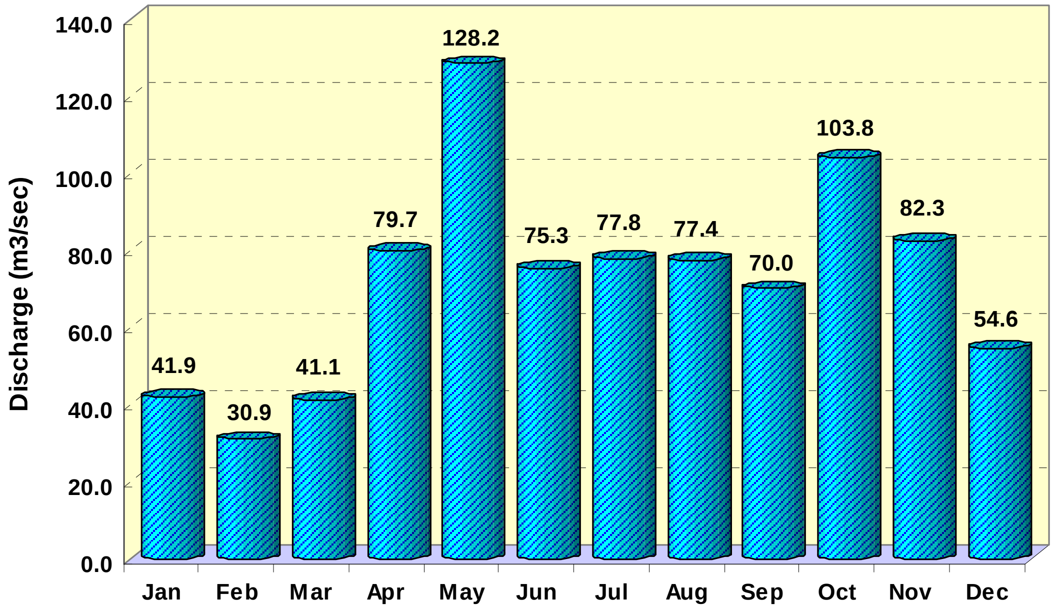


Figure 1.26: Monthly Average River Flow at Weito Bridge Station

The above example of monthly river flow variation for Weito Bridge is characterized by high level of correlation with the precipitation patter in the same area. The flow rates are high in rainy season and lower in dry season. Also the two peaks in flow rates are observed as in the precipitation pattern.

This pattern of river flow is most common among the collected data sets. The data from almost 1/3 of the stations (14 stations) show this pattern. They are : Bedessa, Djidu_Childern, Gidabo_Aposto, Gidabo_Meass, Guder_Hoseaeina, Hamassa_Humbo, Hamassa_Wajifo, Kulfo_Arba Minchi, Melka Oda_Oda, Rinzaf_Butagera, Rinzaf_Butagera, Sala_Dilla College, U_Gelana_Yirga_Cheffie, Gato_Gidole。

c.5.2 Pattern 2

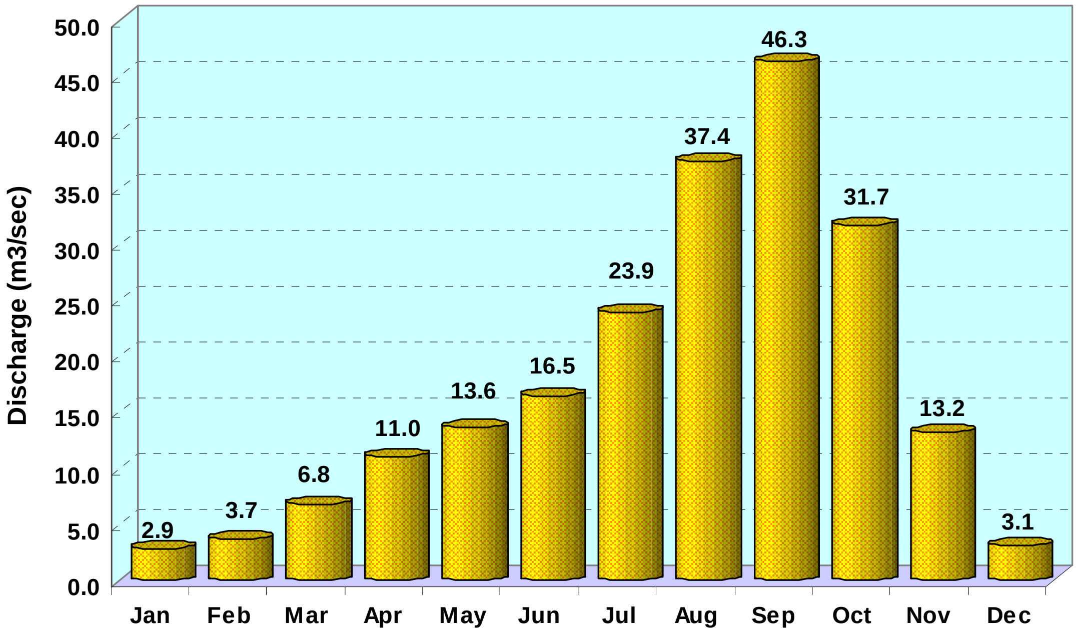


Figure 1.27: Monthly Average River Flow at Bilate Tena Station

This pattern is characterized by very high flow rates in rainy season and low flow rates in dry season. The distinction between the rainy season and dry season is clear as in patter 1 but having only one peak in flow rates in rainy season sets it apart from pattern 1.

The data form the following 14 stations show this pattern : Ashebeka_Sagure, Batena, Bilate_Kulito, Chiufa_Arata, Dedeba_Kuyera, Ferfero_Wulbareg, Gedemso_Langano, Harekelo_Langano, Katar_Abura, Kolla_Alete_ L.Timala_Sagure, Lipiso_L.Langano, Meki_Meki Village Wondo, Weira_Hosaena。

c.5.3 Pattern 3

The example of pattern 3 from 40 Spring stations, shown in Figure 1.28, show quite different features in seasonal variation of flow rates as compared with the previous two. The difference among the months is very small. The reason for this small seasonal variation is considered to be because the data does not include surface water flow component. In other words, most of the flow is formed by groundwater inflow. This also means that the flow, only recharged by groundwater, is classified into spring flow but not river flow.

There are five stations of which the data show this pattern: Lake_Shalla, Tikur Woha_Dato Village, Werka_Wondo, Wosha_Wondo Genet, 40 Spring.

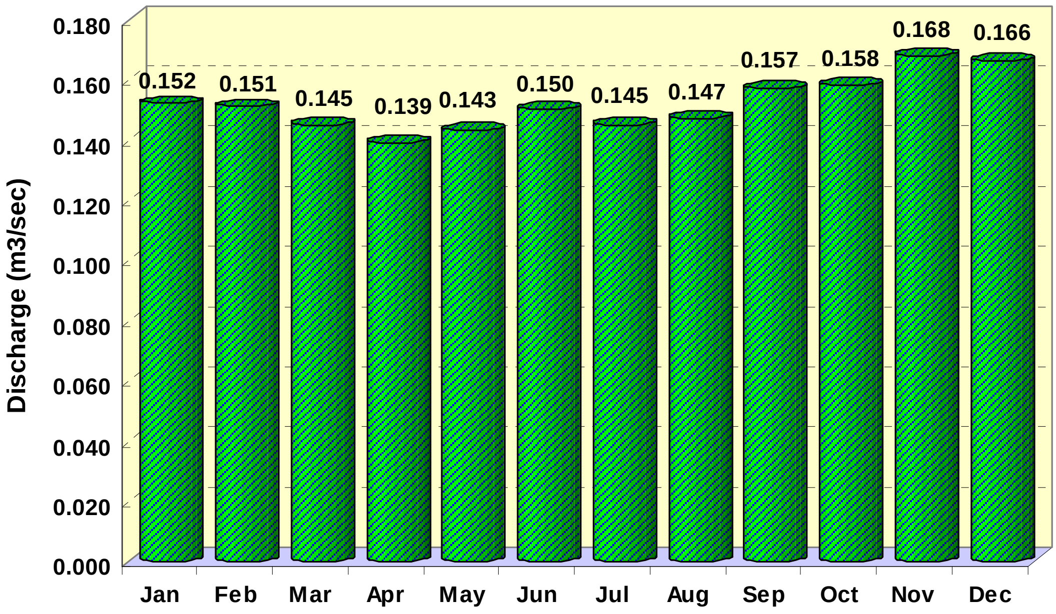


Figure 1.28: Monthly Average Discharge at 40-Spring Station

c.5.4 Pattern 4

This pattern only appears at one station (Wolkesa Assela) and is characterized by low flow rates other than the season (July to September). Since there is only one set of data showing this pattern and thus, can not be used for the analysis. The cause for this pattern is also difficult to examine.

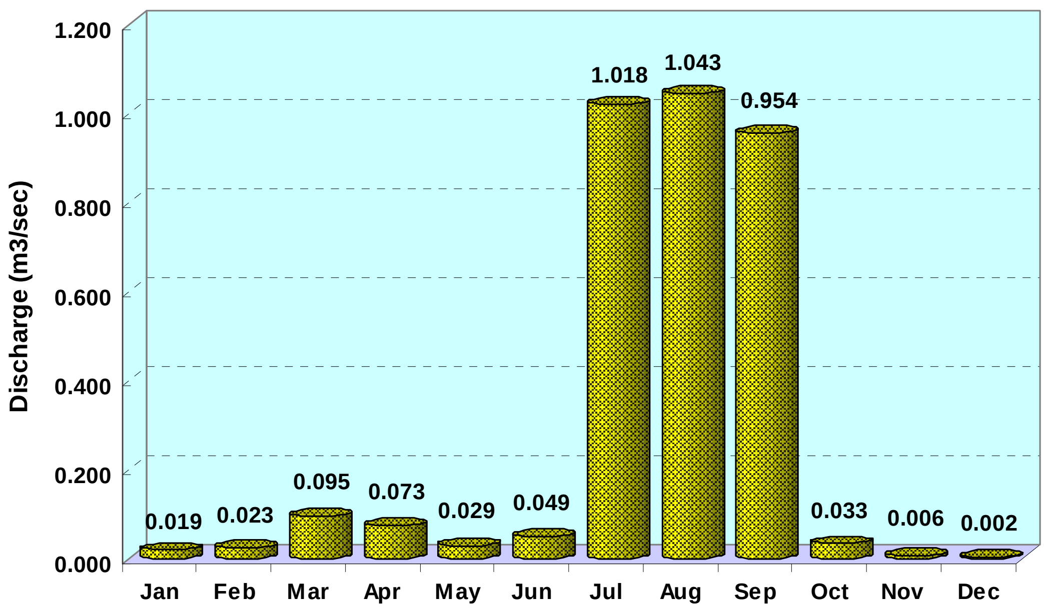


Figure 1.29: Monthly Average River Flow at Wolkesa Assela Station

1.4 Analysis of groundwater recharge

In this section, the amount of groundwater recharge in major sub-basins in the study area will be estimated based on the relation between river flow and groundwater recharge amount. The estimated data will be then used to grasp the available water resources amount for each basin.

1.4.1 Relation between river flow and groundwater flow

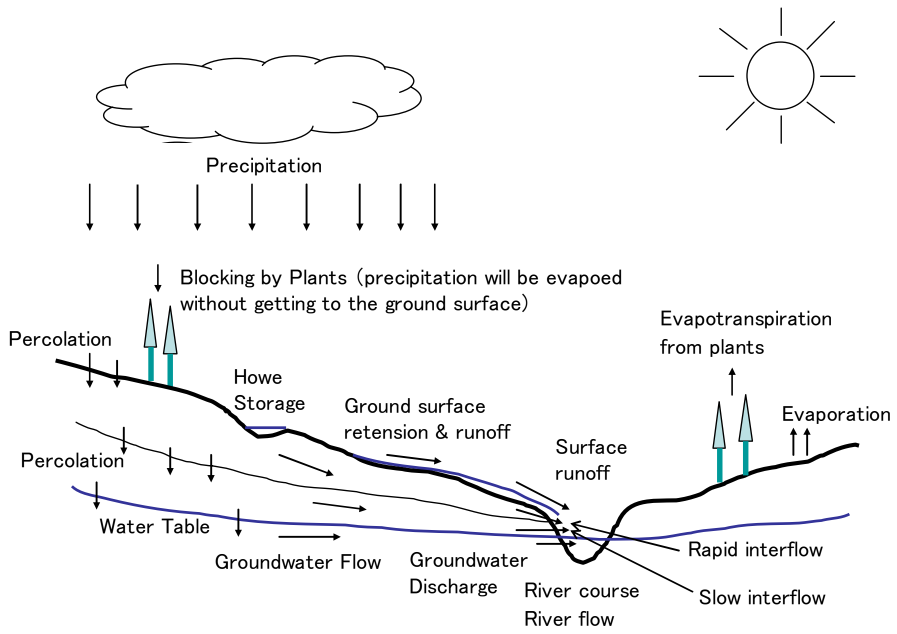


Figure 1.30: Precipitation and Process of River Water Formation

As shown in Figure 1.30, the river water is formed by surface runoff from the precipitation and groundwater discharge to the river. The direct surface runoff can be further divided into the following three components:

- Surface run off that does not infiltrate into the ground and directly flows into river streams
- Rapid interflow that has once infiltrated into the ground but quickly discharge into river streams before it reaches the groundwater table.
- Slow interflow that has once infiltrated into the ground but discharges into river streams before it reaches the groundwater table. This component takes much longer time than the rapid interflow component to discharge into a river.

The groundwater levels, that are recharged by direct precipitation, compared to surface water is usually high. Thus the groundwater usually flows, from higher to lower levels, into river streams.

The direct runoff due to precipitation usually continues only a few hours after the rain stops or for a few days, in the case of large river basins, at longest. The river flow rapidly increases due to inflow of a large amount of water into river streams in a short time.

In contrast, the velocity of flow is much smaller in the case of groundwater inflow although the rate of inflow from the groundwater depends on the permeability of the aquifer and the hydraulic head of the groundwater. Thus, groundwater discharge continues even on days and seasons of no rain. This is how river streams under no-rain conditions are replenished by groundwater inflow.

Based on the mechanism explained above, the river flow can be separated into direct surface runoff component and groundwater inflow component.

1.4.2 Method of groundwater recharge analysis

One of the objectives of this study is to evaluate the groundwater potential in the study area and to formulate a groundwater development plan, especially to supply water to small towns. For this reason, it is very important to grasp the amount of groundwater recharge. There are many methods to directly calculate the groundwater recharge but most reliable ones are to measure directly with a lysimeter or to use the tank model based on the daily precipitation and groundwater level data. However there are neither lysimeter measurement data nor long term groundwater level records that can be used for the analysis. This means the groundwater recharge can not be directly calculated.

On the other hand, the recharge and discharge amounts are more or less equal in a long hydrological cycle. Otherwise the level of groundwater surface is either on the rise or on the decline. This means that if groundwater discharge amount is calculated, the recharge amount can also be estimated. The groundwater discharge is composed of the following four components:

- Discharge into rivers
- Discharge into lakes
- Discharge to outside the basin
- Groundwater use by pumping at wells

The most important component among the above four is considered to be the (groundwater) discharge into river streams and thus, it will be necessary to calculate the amount/ratio of groundwater component in river flows. The following sections discuss the process of separating the groundwater component.

1.4.3 Separation of river flow components (BFI calculation)

The ratio of the groundwater component in a river flow is defined as BFI (Base Flow Index). Many methods have been developed and used to separate the groundwater (base flow) component and direct runoff component from daily river flow data. However the result will be naturally different depending on the method employed. In this study the following two methods (programs) were selected since both are considered to be reliable.

Program 1: **PART** (USGS; 2007). The computer program uses stream flow partitioning to estimate a daily record of groundwater discharge under the stream flow record. The method designates groundwater discharge to be equal to stream flow on days that fit a requirement of antecedent recession, linearly interpolates groundwater discharge for other days, and is applied to a long period of record to obtain an estimate of the mean rate of groundwater discharge.

Program 2: **RAP** (**R**iver **A**nalysis **P**ackage; 2005, from CRC (Cooperative Research Centre for Catchment Hydrology, Monash University Melbourne), AUS) The method of calculating the base flow component of the hydrograph is through the use of a 3-way digital filter as described below.

$$q_{f(i)} = \alpha q_{f(i-1)} + (q_{(i)} - q_{(i-1)})\frac{1+\alpha}{2}$$

$q_{(i)}$ is the original stream flow for the ith sampling instant

$q_{f(i)}$ is the filtered quick flow for the ith sampling instant

$q_{(i-1)}$ is the original stream flow for the previous sampling instant to i

$q_{f(i-1)}$ is the filtered quick flow for the previous sampling instant to i

α is filter parameters

a. Selection of data stations for BFI calculation

There are eight major lakes in the study area. In groundwater modeling 1, one of the eight lakes, Lake Abaya basin was already analyzed to estimate the amount of groundwater recharge within the basin. Therefore the remaining seven lake basins will be analyzed in this section. In order to achieve better accuracy and reliability in the analysis result, the target data stations were selected by the following criteria.

- Stations should be selected from each lake basin
- If several stations are available within the same basin, stations with data sets showing pattern 1 or 2 should be selected.
- If two or more stations showing the same pattern are available, the one with shortest period of missing data and longest period of observation should be selected.

The stations selected by the above criteria are listed in Table 1.23.

Table 1.23: Basic Information on the Stations Selected for River Flow Analysis

Basin	Station	Duration	MD_2	M_Flow
Ziway	Meki_Meki Village	1969 - 2006	8.9%	8.60
Langano	Gedemso_Langano	1995 - 2007	28.6%	1.35
Abijata	NA	--	--	--
Shalla	Djidu_Childern	1983 - 2008	14.0%	5.85
Awassa	NA	--	--	--
Abaya	No Need	--	--	--
Chamo	NA	--	--	--
Chew Bahir	Weito_Bridge	1980 - 2007	16.1%	72.17

MD_2: Percentage of missing data except those years without any observation data.
M_Flow: Average river flow in unit of m^3 / sec.

Out of the seven lake basins targeted for the analysis, three of them did not have appropriate data stations for the purpose: Abiyarta and Chamo basins do not have any stations within the basin. Awassa basin have 3 stations but all show patten 3 (spring type) and can not be used for the analysis.

b. Selection of data period and data complementation for BFI calculation

Table 1.20 shows the data observation period and the ratio of missing data after exclusion of non-observation years. The selected four stations all satisfies the criteria that the stations should have long period of observation of data but they all have problem of relatively high ratio of period of missing data.

Although it is desirable to use the relationship with the stations in the surrounding areas, such relation was not recognized. Thus, the data was complemented by the auto-correlation method to analyze the data of average daily flow. However, this method of data complementation may introduce relatively high level of error in the result of analysis targeting separation of river flow components. Thus, the following criteria were applied to select the period of available data sets for analysis.

- Data missing period is less than 3% within consecutive one year of observation period.
- Data missing period should be within dry season

The data periods for analysis were selected from the series of data by the above criteria for each station and they are listed in Table 1.24.

Table 1.24: Selected Periods for River Flow Regression Analysis

Station	Year	M_Day
Meki_Meki Village	1969-1976	0
	1979-1980	0
	1982-1984	0
	1987-1991	0
	1993	0
	1997-2001	13
Gedemso_Langano	1997-2000	0
	2004	0
	05/09-07/08	0
Weito_Bridge	82/05-85/04	4
	94/07-96-06	0
	1997-1999	0
	00/08-03/07	0
	2005-2006	0
Djidu_Childern	83/12-88/11	0
	1990-1991	0
	1997-2002	0
	2004-2006	0

M_day: Missing data days in the corresponding analysis period.

c. Example of flow component separation (BFI calculation)

Figure 1.31 shows the longest data for analysis from Meki Village station in Ziway lake basin that cover from 1969 to 1976. The result of flow components separated from the eight year daily river flow data series is shown.

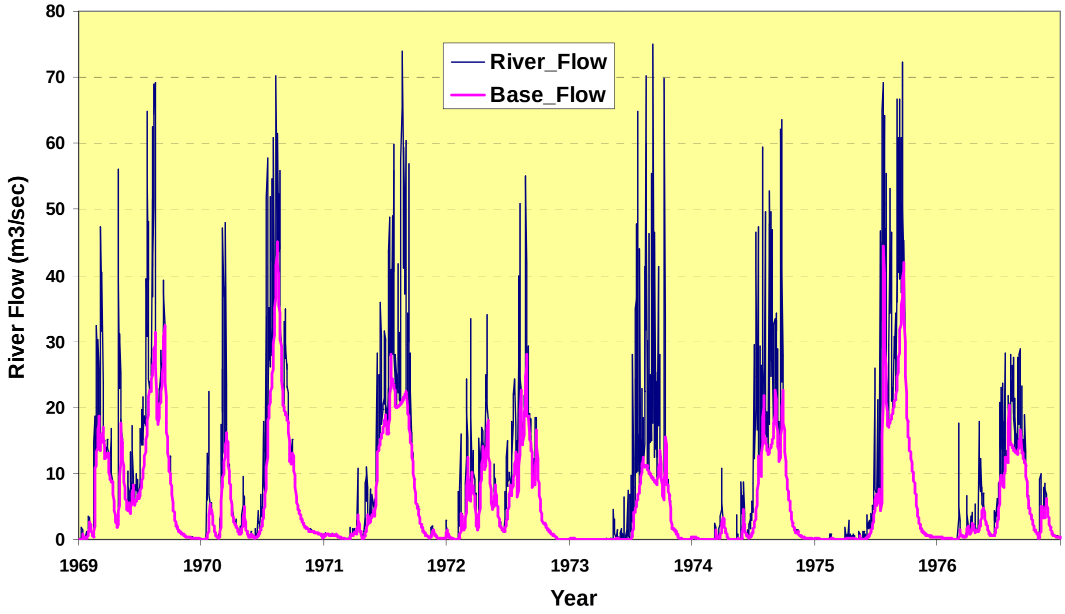


Figure 1.31: Example of Result of River Flow Separation for Meki Meki Village Station

Figure 1.32 shows the result of flow component separation from the longest data series of the representative station of Gedemso Langano in Langano lake basin. The separated flow components based on the four year daily flow data from 1997 to 2000 are shown on the graph.

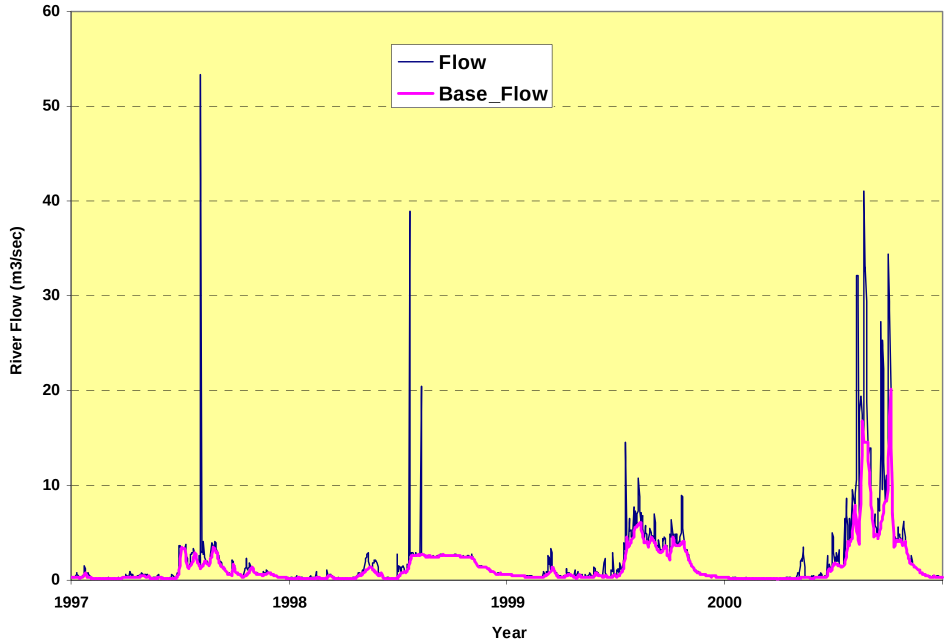


Figure 1.32: Example of Result of River Flow Separation for Gedemso Langano Station.

Figure 1.33 shows the result of flow component separation analysis from the longest data period at Weito Bridge station in Chew Bahir lake basin. The separated flow components are shown on the graph based on the 3-year daily flow data from 1997 to 1999.

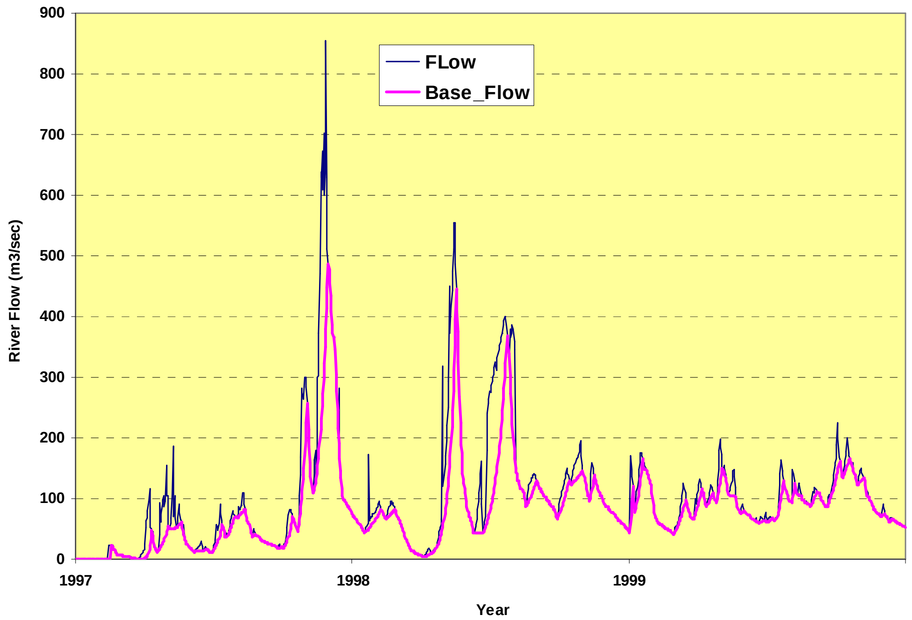


Figure 1.33: Example of Result of River Flow Separation in Station Weito Bridge.

Figure 1.34 shows the result of flow component separation analysis from the longest data sets at Djidu Childern station in Shalla lake basin. The separated flow components are indicated on the graph based on the 6 year daily flow data series covering 1997 to 2002.

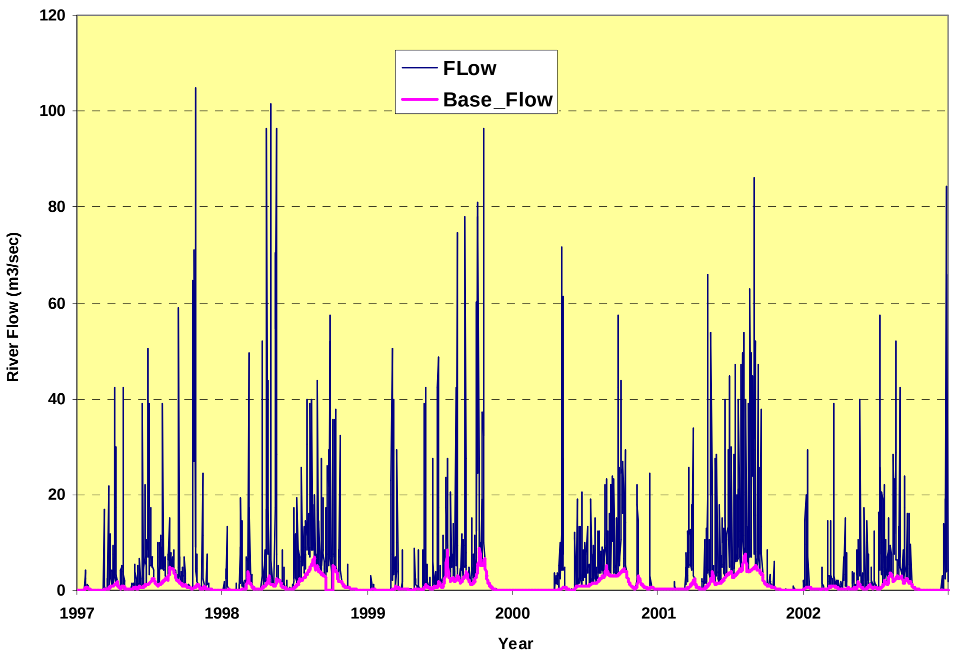


Figure 1.34: Example of Result of River Flow Separation for Djidu Childern Station.

d. Result of flow separation analysis (BFI calculation)

The result of flow separation analysis (BFI calculation) for each representative station in each lake basin is compiled in Table 1.25. In addition, in the groundwater modeling 1, the BFI (base flow index) for Lake Abaya basin was found to be 0.624.

Table 1.25: Calculated BFI Values from Flow Separation Analysis

Station	Year	PART	RAP
Meki_Meki Village	1969-1976	0.65	0.53
	1979-1980	0.70	0.53
	1982-1984	0.68	0.52
	1987-1991	0.72	0.55
	1993	0.79	0.53
	1997-2001	0.64	0.48
	Average	0.68	0.52
	Adoption	0.60	
Gedemso_Langano	1997-2000	0.69	0.54
	2004	0.76	0.59
	05/09-07/08	0.81	0.58
	Average	0.73	0.56
	Adoption	0.65	
Weito_Bridge	82/05-85/04	0.71	0.54
	94/07-96/06	0.88	0.76
	1997-1999	0.80	0.63
	00/08-03/07	0.91	0.74
	2005-2006	0.83	0.62
	Average	0.82	0.65
	Adoption	0.74	
Djidu_Childern	83/12-88/11	0.29	0.33
	1990-1991	0.24	0.31
	1997-2002	0.21	0.29
	2004-2006	0.20	0.30
	Average	0.24	0.31
	Adoption	0.27	

Part: Result from the program of PART(USGS, 2007).
RAP: Result from the program of RAP (2005, AUS)

In this study two different methods of flow component separation analysis (BFI calculation) were employed to avoid biased results. The difference between the two methods range, as shown in Table 1.25, from a few percent to 20%. Therefore, the values of BFI for the following analysis were taken as the average of the two values from the two programs.

Also the analysis was conducted for several data series of different length and period. Thus, the BFI was calculated by taking the weighted average of the resultant values from all the data sets. The following formula was used to find the BFI:

$$\mathbf{BFI\_M = \Sigma(BFI\_i \times Years\_i) / \Sigma Year\_i}$$

whereas
BFI_M: Averaged BFI for the entire analysis period (see Table 1.25)
BFI_i: BFI in a single data period for analysis
Year_i: Number of years for the single data period for analysis

1.4.4 Verification of the result of flow separation (BFI values)

The result of the BFI determination for the five lake basins out of the eight in the rift valley area is presented in Table 1.26.

Table 1.26: BFI Values for 5 Lake Basins

Basin	Station	BFI
Ziway	Meki_Meki Village	0.60
Langano	Gedemso_Langano	0.65
Shalla	Djidu_Childern	0.27
Abaya	Bilate_Tena	0.62
Chew Bahir	Weito_Bridge	0.74

The result indicates that four out of the five stations have BFI values between 60% and 74% and have relatively similar basin characteristics. On the other hand, the value for Djidu Children station in Lake Shalla basin has a much smaller value of 27%.

The mechanism of river flow formation suggests that there are several factors controlling the amount of recharge into river streams by groundwater. Possible reasons for the small value of BFI for Djidu Children station was investigated in terms of these factors as follows.

A. Size of the basin

Hydrologically, the value of BFI increases with the size of the basin because of the following two reasons.

- In large basins, the rainfall in the basin tends to be no-uniform. Thus, if some rain occur in one part of the basin while no rain is occurring in other parts of the basin, that will limit the increase in flow rate in river streams. This will cause relative increase in the ratio of groundwater component in the river flow.
- In large basins, the stations (on the main course of the river) tend to be far away from the catchment areas. Thus the precipitation in such distant catchment areas will form less interflow that contributes to river water discharge.

In order to evaluate the effect of basin size on the value of BFI, the catchment area in the upstream of the selected flow observation stations was calculated with the use of SRTM data (90m mesh; USNASA). The result is shown in Figure 1.35.

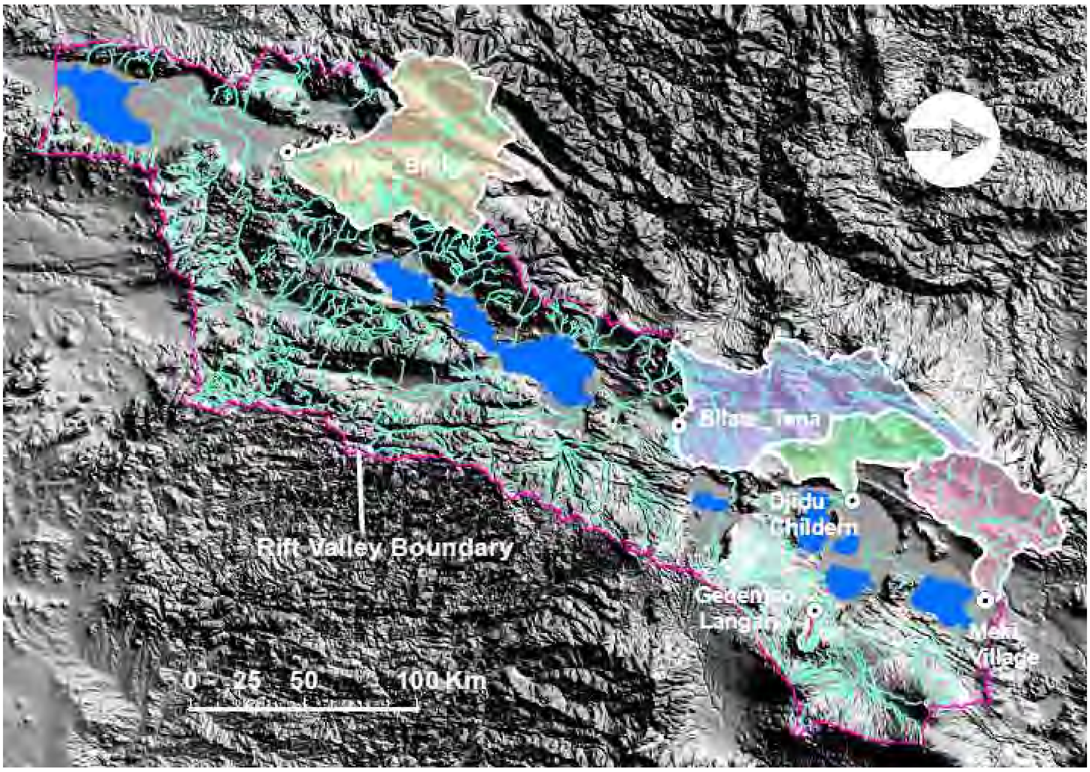


Figure 1.35: Catchment Boundaries of the 5 Basins Delineated for BFI Analysis

Table 1.27 compiles the calculated area of catchment located upstream of each of the five stations employed for the analysis.

Table 1.27: Relation between BFI and Basin's Area

Basin	Station	BFI	Area	M_Flow
Langano	Gedemso_Langano	0.65	82.8	2.0
Shalla	Djidu_Childern	0.27	1,461.2	5.8
Ziway	Meki_Meki Village	0.60	2,213.7	8.6
Abaya	Bilate_Tena	0.62	3,935.0	17.6
Chew Bahir	Weito_Bridge	0.74	4,499.0	72.2

Area: Upstream district of the river flow observation station in unit of km^2.
M_Flow: Average river flow in unit of m^3 / sec.

As seen in the table, Djidu Children station has the smallest BFI value among them but its upstream catchment area is not as large as most other basins of larger size. Moreover, its upstream catchment area is more than 10 times larger than that of Gedemso Langano station that has the smallest upstream catchment. Therefore, the size of catchment area is not the determining factor for the small BFI value.

B. Frequency of precipitation

The direct run off component in the river flow is controlled by precipitation. Even with relatively comparable annual precipitation, however, the occurrence of flow peaks depend on the frequency of intensive rain that will exceed the permeability of the land. From this point of view, rainfall frequency analysis was conducted for some rainfall stations in the basins selected for BFI analysis to find the frequency of rainfall that may cause surface runoff in the study area. The locations of the stations are shown in Figure 1.36.

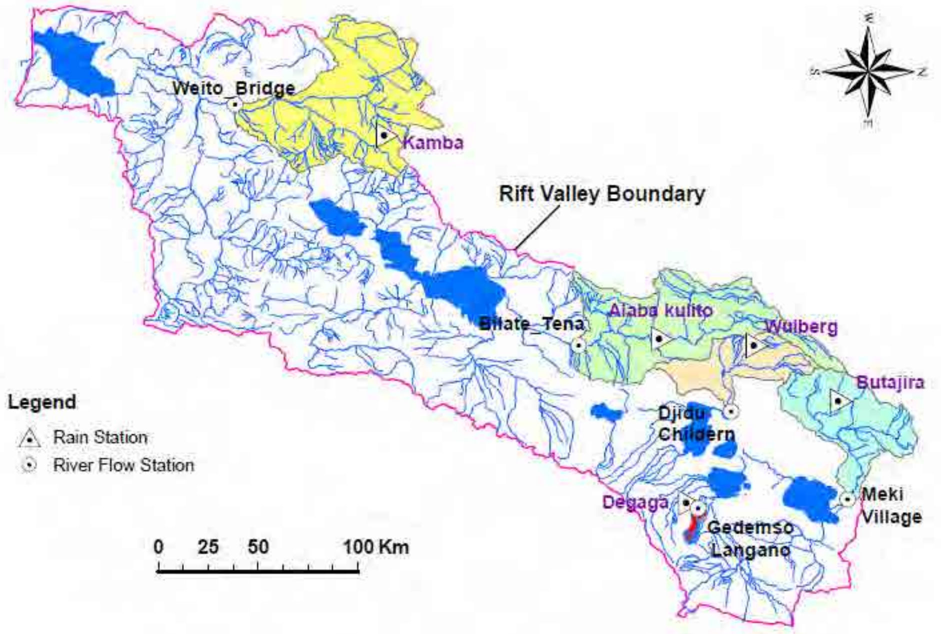


Figure 1.36: Location of the Rainfall Stations Used for Rainfall Frequency Analysis

Table 1.28 compiles the number of observations made during the observation period, and the calculated number of days when an intensive rainfall enough to cause surface runoff is expected to occur. For rainfall intensity, different levels from 10mm/day to 40mm/day were considered.

Table 1.28: Result of Frequency Analysis for Intensive Rainfall

Basin	Langano		Shalla		Ziway		Abaya		Chew Bahir	
BFI_Station	Gedemso_L.		Djidu_C.		Meki_V.		Bilate_Tena		Weito_Bridge	
Rain_Station	Degaga		Wulberg		Butajira		Alaba kulito		Kamba	
BFI	0.65		0.27		0.60		0.62		0.74	
	Days	%	days	%	days	%	days	%	days	%
T_R_Data	9,536	100	13,453	100	15,140	100	7,973	100	8,033	100
>10 Rain days	900	9.4	1,779	13.2	1,537	10.2	700	8.8	1,116	13.9
>20 Rain days	286	3.0	455	3.4	592	3.9	279	3.5	309	3.8
>30 Rain days	100	1.0	124	0.9	250	1.7	102	1.3	113	1.4
>40 Rain days	37	0.4	39	0.3	119	0.8	47	0.6	39	0.5

T_R_Data: Total real observed rainfall data (days)
>OO Rain days : Days with rainfall over OO mm.

As shown in the table above, no clear difference is recognized among the stations in terms of frequency of strong rain.

C. Flow rate in dry season (low water period)

In accordance with the change in monthly rainfall, surface runoff into the river occur mostly in the rainy season and the river stream is supplied only by groundwater discharge during the dry season. The low water period in the dry season corresponds to November to March can be seen in the flow patterns discussed earlier.

Figure 1.37 presents the result of probability analysis conducted based on the data from the low water period of the five stations. The low water flow at Djidu Children station is several to 10 times smaller than the low water flows from the three basins (Weito_Bridge, Gedemoso_Langano, Billate River_Tena) of relatively large basin area. The result is considered natural. However, the values of low water flow are still smaller even compared with those from Gedemso langano station that has a basin area of less than 1/10. This result simply indicates the amount of recharge into river flow from groundwater is small in this basin.

If the groundwater flow component flowing outside the basin is ignored, small discharge from groundwater into the river flow also indicates groundwater recharge in the basin is small. On the other hand, the degree of recharge to the groundwater is affected by some factors such as precipitation amount, rainfall frequency, rainfall intensity, and geological condition. The series of analyses conducted in the study revealed that the variation in precipitation amount and its frequency is relatively minor and thus, the small amount of groundwater discharge into the river may be attributed to hydrogeological conditions, namely permeability of the surface formations, in the area.

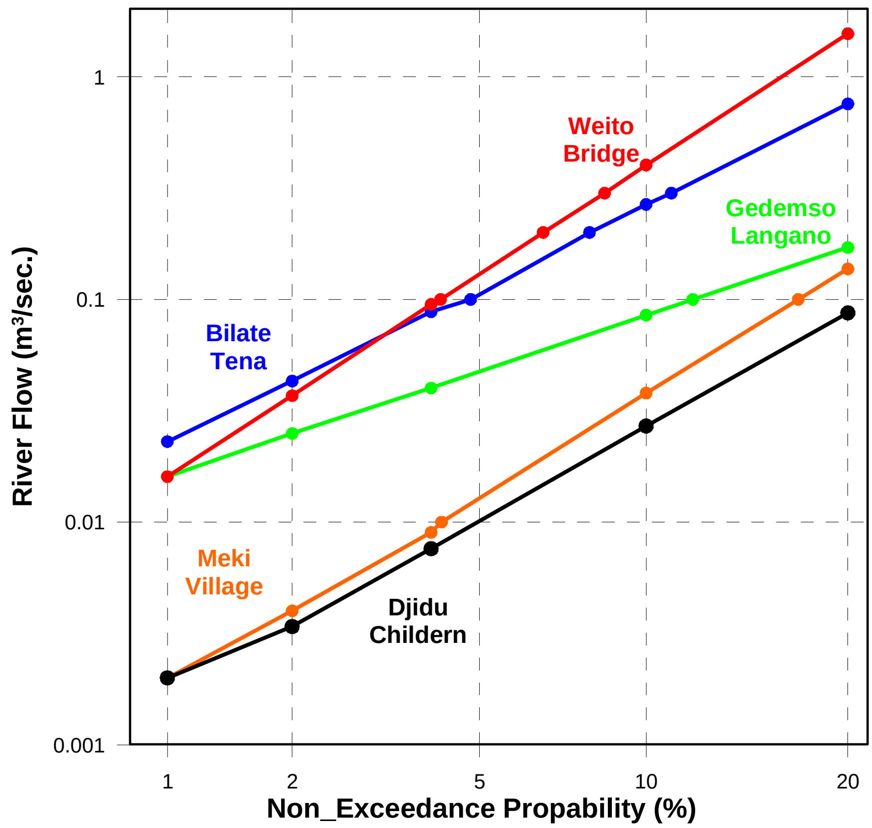


Figure 1.37: Probability Analysis of Low Water Flow at 5 Stations

1.4.5 Groundwater resource amount in rift valley area

In this section, the amount of groundwater recharge in major lake basins will be estimated based on the BFI values calculated in the previous sections. The meaning of "groundwater resources amount" is different from the amount of groundwater contained in underground aquifers in an area. One of the many basic items of consideration in planning of groundwater development is to make sure the groundwater use amount will not exceed the recharge amount. Excessive use of groundwater may bring about drawdown of water table or drying of groundwater in the area. From this point of view, the groundwater resources amount in this section is used to mean groundwater recharge amount.

In the pervious discussion of evaporation analysis from the lakes, the amount of water resources in the rift valley lakes basin was found to be 3,246.5 Mm^3 equivalent to 364.8 m^3 per capita. This amount is a combination of surface water and groundwater components and the groundwater component is made of the base flow component in the river flow. Furthermore, this base flow component was separated from the surface run off component in the river flow based on the daily flow data. All these analysis results were compiled to calculate the amount of groundwater recharge (GWR) in each lake basin in the rift valley area. The following formula was used to find the GWR.

$$GWR = \Sigma (E_{i\_net} \times BFI_i)$$

whereas
GWR: Groundwater recharge amount
E_{i_net}: Net evaporation from each major lake
BFI_i: Base flow index for each major lake basin

However, three out of the eight major lake basins (Abijata, Awassa and Chamo) do not have any stations with which BFI of the basins can be analyzed. Therefore, BFI values of the three lake basins were calculated with the above formula using the average of the surrounding lake basins.

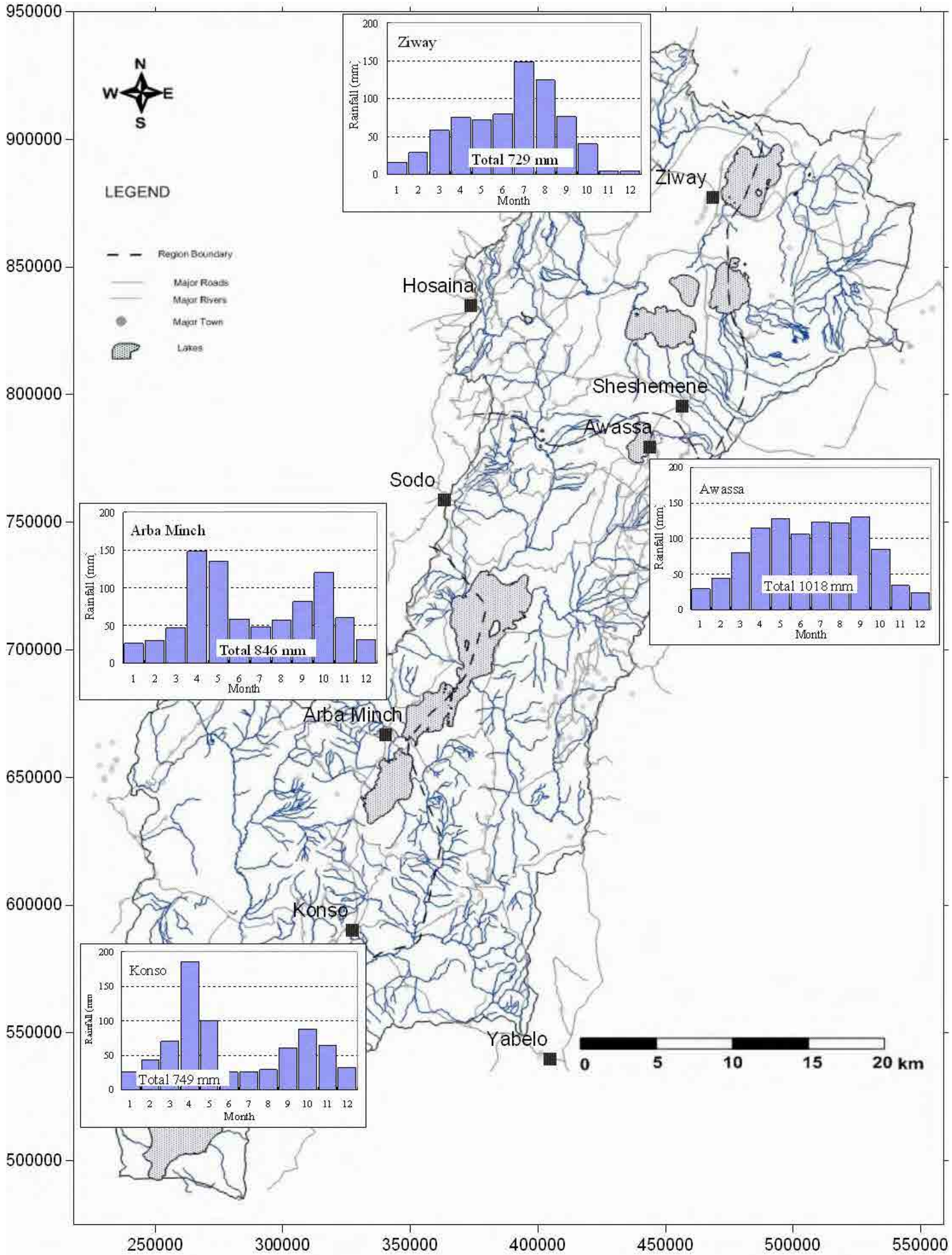
In reality the water resources consumption in the rift valley lakes basin is not only evaporation from the lakes, but also evaporation from river routes and use of water for irrigation. On the other hand, as it was found in groundwater modeling 1, the water consumption by these phenomena and activities correspond to about 5% of the total consumption.

It is nearly impossible to delineate the ratio of surface water and groundwater in this small portion of water consumption because the analysis will require not only data on natural conditions but also various types of socio-economical and water use data. Meanwhile, its ratio to the entire water resources is as small as 5% and the errors based on the data will also be contained within 5%. In this sense, it was assumed that a half of it, 2.5%, is attributed to consumption of groundwater and its contribution is added to the result of groundwater recharge amounts calculated in the previous section. The final results are compiled in Table 1.29.

Table 1.29: Groundwater Recharge Amount in Major Lake Basins in Rift Valley Lakes Basin

Name	$Evapo_{net}$	BFI	GWR	Others	Total
Abaya	585.1	0.62	362.8	14.6	377.4
Abijata	106.5	0.60	63.9	2.7	66.6
Awassa	91.6	0.45	40.8	2.3	43.1
Chamo	282.2	0.68	191.9	7.1	199.0
Chew Bahir	412.7	0.74	305.4	10.3	315.7
Langano	423.0	0.65	275.0	10.6	285.5
Shalla	185.9	0.27	50.2	4.6	54.8
Ziway	977.7	0.60	586.6	24.4	611.1
Others	19.5	--	12.1	0.5	12.6
Total	**3084.3**	**--**	**1888.6**	**77.1**	**1965.7**

$Evapo_{net}$: Net Evaporation amount from lakes in rift valley area (Mm^3).
BFI: Base flow index.
GWR: Groundwater recharge amount (Mm^3).
Others: Groundwater recharge amount used by all other water consumption (Mm^3).
Total: Total groundwater recharge amount for the lakes (Mm^3).



Note: the data for the graphs was compiled based on aaproximately 30 year rainfall data

Figure 1.38	Monthly Rainfall Distribution Pattern in the Study Area
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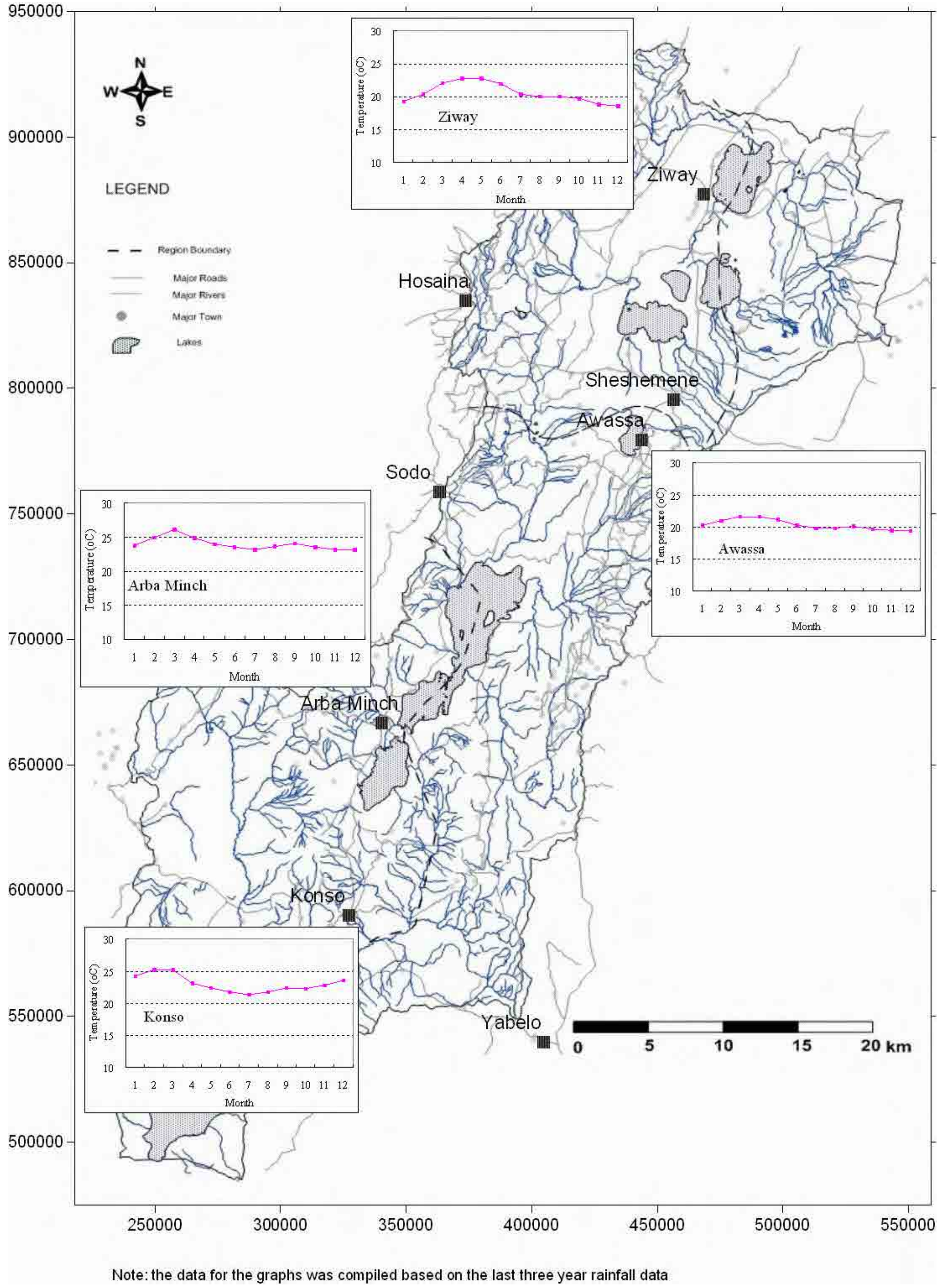

Figure 1.39	Monthly Temperature Distribution Pattern in the Study Area
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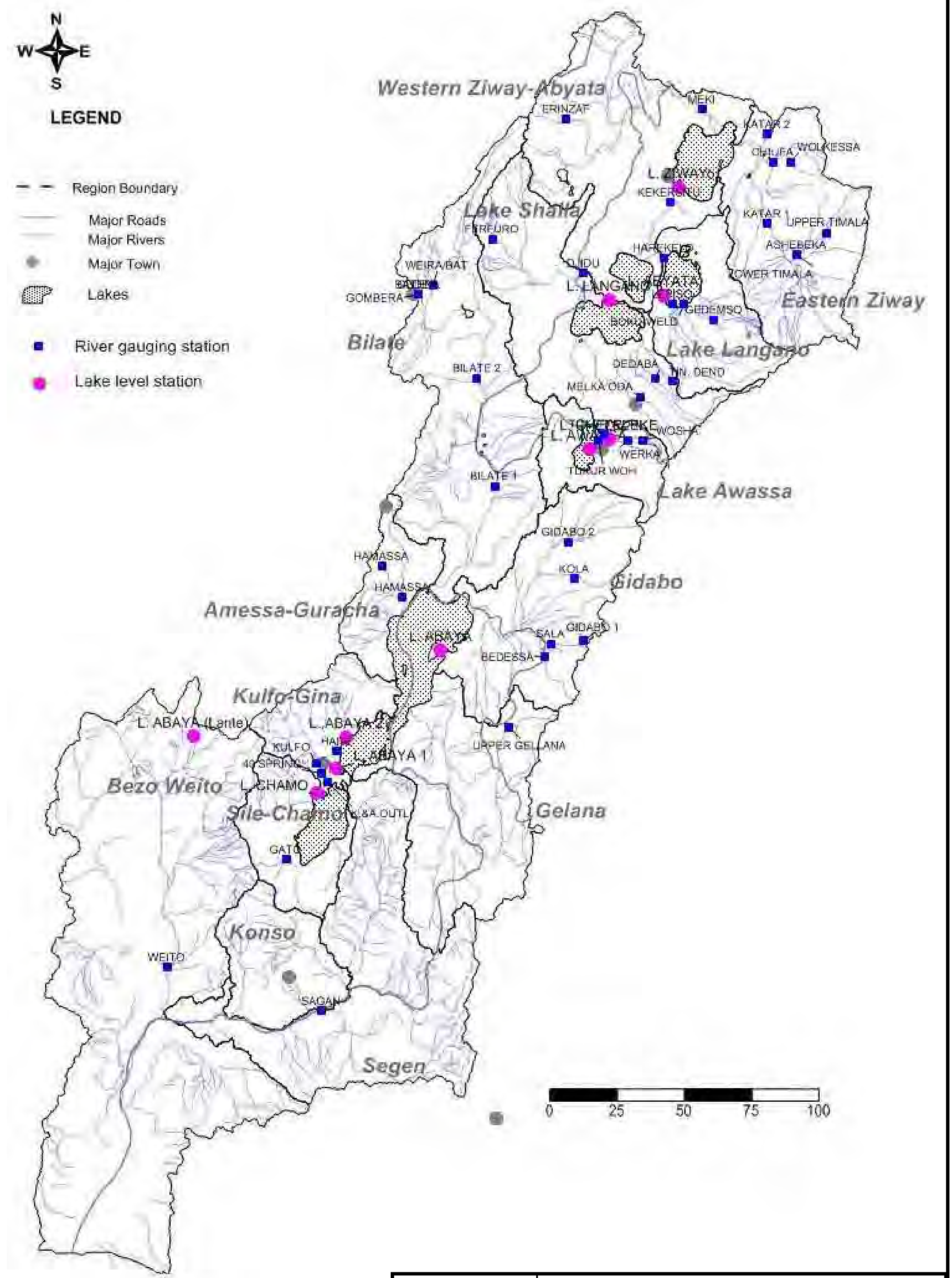

Figure 1.40	Location of Hydrological Stations in Sub-basin
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