The Federal Democratic Republic of Ethiopia
Ministry of Water, Irrigation and Electricity

THE PROJECT FOR GROUNDWATER RESOURCES ASSESSMENT IN THE MIDDLE AWASH RIVER BASIN IN THE FEDERAL DEMOCRATIC REPUBLIC OF ETHIOPIA

FINAL REPORT
SUPPORTING REPORT

December 2015

Japan International Cooperation Agency
Kokusai Kogyo Co., Ltd.

Composition of the Report

Executive Summary

Main Report

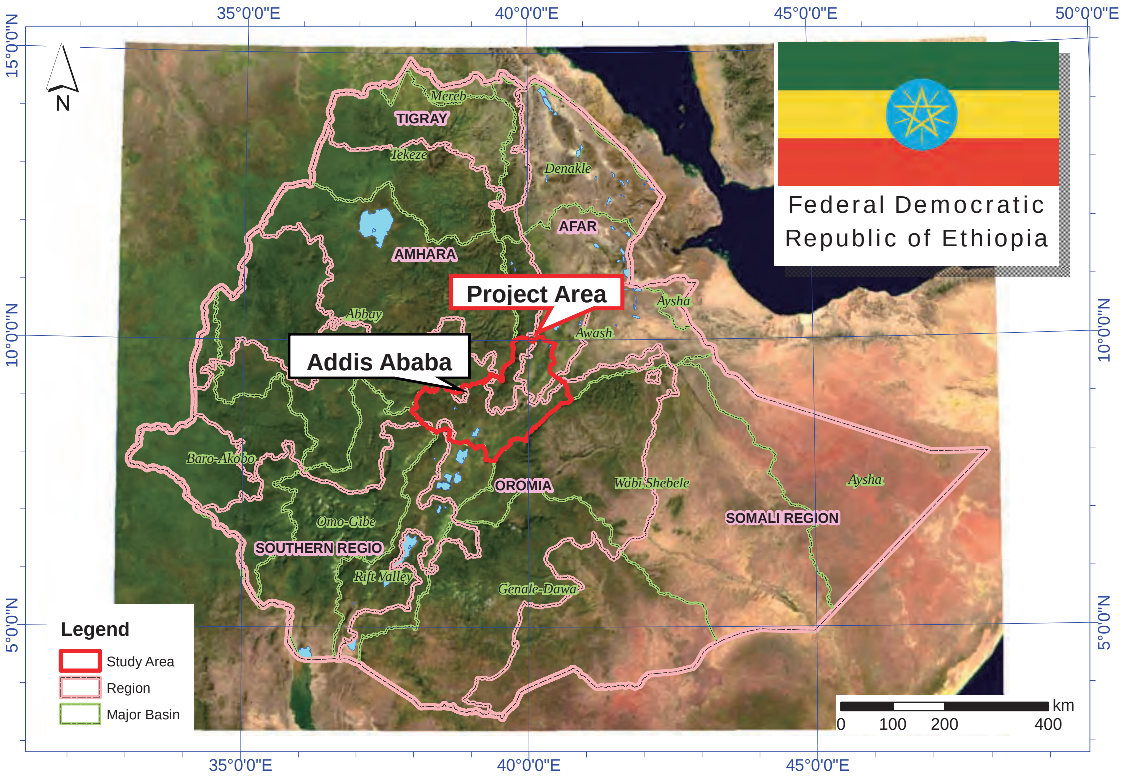
Supporting Report

Data Book

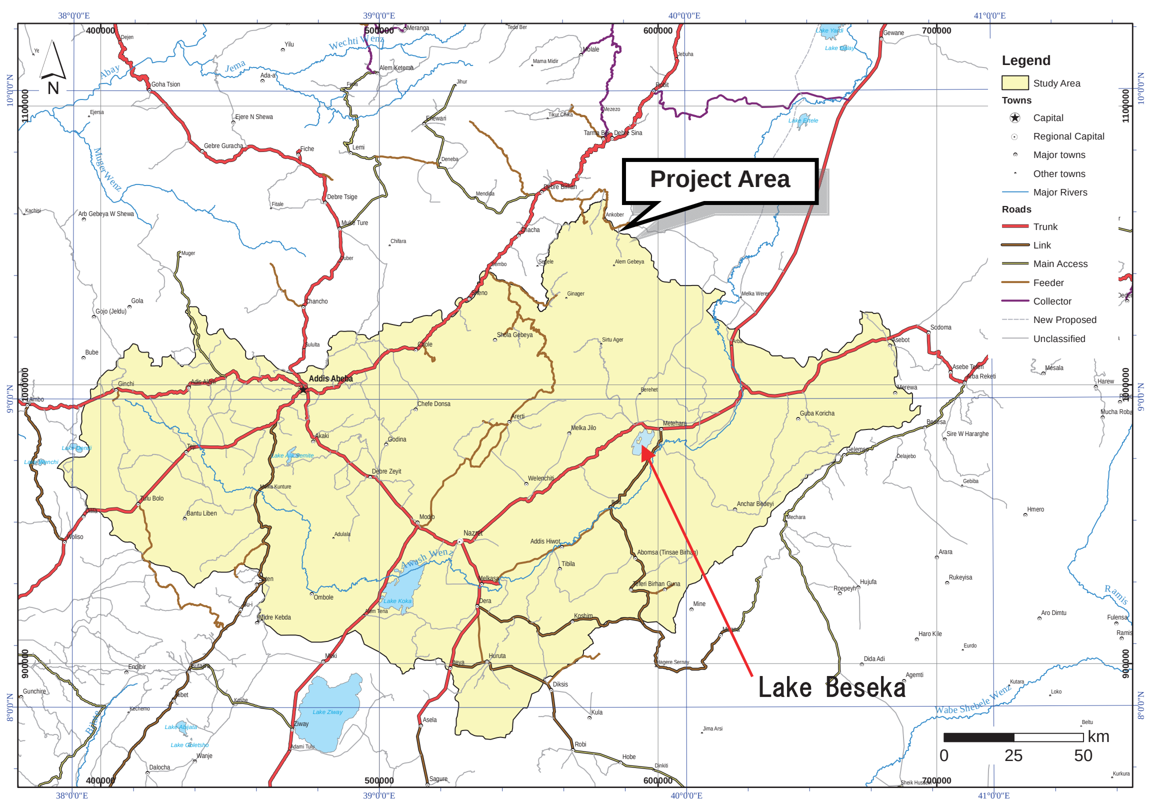
Geological and Hydrogeological Maps

This Report is prepared based on the price level and exchange rate of July 2015.
The exchange rate is:

US$1.0 = ETB20.6298 = JPY123.80



Location of the Study Area



The Middle Awash River Basin

LOCATION MAP

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Abbreviations

AAU	Addis Ababa University
AGRAP	Alidge Groundwater Resources Assessment Project
AIDS	Acquired Immune Deficiency Syndrome
ALOS	Advanced Land Observing Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASTER-GDEM	ASTER-Global Digital Elevation Model
BFI	Base Flow Index
CAD	Computer Aided Design (System)
CDE	Center for Development and Environment, Ministry of Agriculture
CFC	Chloride Fluoride Carbon
CREC	China Railway Engineering Corporation
CSA	Central Statistical Agency
CSE	The Conservation Strategy of Ethiopia
C/P	Counterpart (organization or personnel)
DB	Datebase
DCI	Ductile Cast Iron
DEM	Digital Elevation Model
DF/R	Draft Final Report
DTH	Down-the-hole Hammer
DWL	Dynamic Water Level
EA	Environmental Assessment
EC	Electric Conductivity
EEPCO	Ethiopia Electric Power Corporation
EGRAP	Ethiopian Groundwater Resources Assessment Program
EIA	Environmental Impact Assessment
EIGS	Ethiopian Institute of Geological Survey, now renamed as Geological Survey of Ethiopia (GSE)
EL	Elevation
ELC	Elc electroconsult milano and Geotermica italiana pisa, Italia (an Italian Consultant)
ELSA	Equilibrium Lake Surface Area
EMA	Ethiopia Mapping Agency
ENGDA	Ethiopian National Groundwater Database
ENGWIS	Ethiopian National Groundwater Information System
EPA	Environmental Protection Agency, now renamed as Ministry of Environment and Forest (MEF)
EPC	Environmental Protection Council
ERA	Ethiopian Road Authority
ERC	Ethiopian Railway Corporation
ESA	Ethiopian Standard Agency
ESIA	Environmental and Social Impact Assessment
ET	Evapotranspiration
EWCA	Ethiopian Wildlife Conservation Authority
EWTEC	Ethiopia Water Technology Center, now renamed as Ethiopia Water Technology Institute (EWTI)
EWTI	Ethiopia Water Technology Institute, formerly known as Ethiopia Water Technology Center (EWTEC)
F/R	Final Report
FAO	Food and Agriculture Organization of the United Nations
FAO-AGLW	FAO Water Resource, Development and Management Services
FDM	Finite Difference Method
FEM	Finite Element Method
GD	Groundwater Directorate (of MoWIE)

GDP	Gross Domestic Product
GHB	General Head Boundary
GIS	Geographical Information System
GL	Ground Level
GNI	Gross National Income
GPS	Global Positioning System
GSE	Geological Survey of Ethiopia
GSP	Galvanized Steel Pipe
GTP	Growth and Transformation Plan
GWR	Groundwater Recharge
HIV	Human Immunodeficiency Virus
IAEA	International Atomic Energy Agency
IC/R	Inception Report
IEE	Initial Environmental Examination
IMF	International Monetary Fund
INGEIS	Instituto de Geocronología y Geología Isotópica (Institute of Geochronology and Geology, Argentine)
ISO	International Standard Organization
ISODATA	The Iterative Self-Organizing Data Analysis Technique
IT/R	Interim Report
ITCZ	Inter-tropical Convergence Zone
JICA	Japan International Cooperation Agency
LEL	Local Evaporation Line
LMWL	Local Meteoric Water Line
M&E	Monitoring and Evaluation
M/M	Minutes of Meeting
MCM	Million Cubic Meter
MDGs	Millennium Development Goals
MEF	Ministry of Environment and Forest, formerly known as Environmental Protection Agency (EPA)
MER	Main Ethiopian Rift
MOA	Ministry of Agriculture
MoWR	Ministry of Water Resources, now renamed as Ministry of Water, Irrigation and Electricity (MoWIE)
MoWE	Ministry of Water and Energy, now renamed as Ministry of Water, Irrigation and Electricity (MoWIE)
MoWIE	Ministry of Water, Irrigation and Electricity, formerly known as Ministry of Water, Irrigation and Energy(MoWIE), Ministry of Water and Energy (MoWE) or Ministry of Water Resources (MoWR)
MSE	Metehara Sugar Estate
MWL	Meteoric Water Line
NASA	National Aeronautics and Space Administration, USA
NGI	National Groundwater Institute
NGO	Non-Governmental Organization
NMA	National Meteorology Agency
OLEPB	Oromia Land and Environmental Protection Bureau
ORP	Oxidation and Reduction Potential
O(R)WMEB	Oromia (Regional) Water, Material and Energy Development Bureau
OWNP	One WASH National Program
OWWDSE	Oromia Water Works Design and Supervision Enterprise
P/R	Progress Report
PA	Preliminary (Environmental) Assessment
PASDEP	Plan for Accelerated and Sustained Development to End Poverty
PC	Personal Computer

PPP	Purchasing Power Parity
PRSP	Poverty Reduction Strategy Paper
PVC	Polyvinyl Chloride
R/D	Record of Discussions
REA	Regional Environmental Agencies
RESTEC	Remote Sensing Technology Center of Japan
RVLB	Rift Valley Lakes Basin
SC	Steering Committee
SCM	Steering Committee Member or Steering Committee Meeting
SDPRP	Sustainable Development and Poverty Reduction Program
SEA	Strategic Environmental Assessment
SFGS	Streamflow Gauging Station
SP	Spontaneous potential
SPOT	Satellite Pour l'Observation de la Terre (French Satellite for Earth Observation)
SRTM	Shuttle Radar Topography Mission
SS	Suspended Solids
TDS	Total Dissolved Solids
TEM	Transient (or Time-domain) Electromagnetic Method
TIR	Thermal Infrared
TM	Thematic Mapper
TOR	Terms of Reference
TU	Tritium Unit
TWSSO	Town Water Supply Service Office
TWSSSE	Town Water Supply and Sewerage Service Enterprise
UAP	Universal Access Program
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children’s Fund
uPVC	Unplasticized Polyvinyl Chloride
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
UTM	Universal Transversal Mercator
VES	Vertical Electrical Sounding
VIP	Ventilation Improved Pit
WASH	Water Supply, Sanitation and Hygiene Program
WB	World Bank
WC	Water Committee
WFB	Wonji Fault Belt
WHO	World Health Organization
WSDP	Water Sector Development Program
WSSM	Water Supply and Sanitation Master Plan
WWDSE	Water Works Design and Supervision Enterprise
WWMEO	Woreda Water, Mineral and Energy Office
ZWMEO	Zonal Water, Mineral and Energy Office

Project Photos (1/5)

Discussion of IC/R

The discussions held on 5 Nov. 2013 were participated by Ministry of Water, Irrigation and Electricity and Geological Survey of Ethiopia. The M/M was exchanged on 11 Nov

Project Introduction

Introducing the outline of the Project to the stakeholder when purchasing the hydrological information.

Site Visit (1)

Discussion between counterparts and experts regarding the construction period of the railway during the site visit to Lake Beseka.

Site Visit (2)

Currently, the water is being discharged to Awash River by a canal at the eastside of the lake as a countermeasure for water level rise.

Geophysical Survey (1)

The observation drilling sites were selected based on the resistivity information (200 m depth) of underground obtained from the geophysical survey (VES).

Geophysical Survey (2)

The observation drilling sites were selected based on the resistivity information (400 m depth) of underground obtained from the geophysical survey (TEM).

Project Photos (2/5)

Geological Survey (1)

The C/P from MoWIE has accompanied the experts in the geological survey for at least 3 months to finalize the geological map.

Geological Survey (2)

Megacha highly welded tuff that overlies Bofa Basalt to the west of Bofa.

Socio-Economic Survey

Focus Group discussions regarding water use status at Kinteri Town of Oromia Region.

Water Usage Inventory Survey (1)

Survey of existing water facilities at Geldiya Town in Oromia Region.

Water Usage Inventory Survey (2)

Situation at the public water tap of Areda Town of Oromia Region. Twenty litres of water cost around 2 Japanese Yen.

Sampling for IAEA Analysis

The tubing method of sampling Helium gas using copper pipe was instructed in order to facilitate IAEA stable isotope analysis.

Project Photos (3/5)

First C/P Meeting

Discussions on P/R1 held on 24 April 2014, with participants from the Ministry of Water, Irrigation and Electricity and Oromia Region. The M/M was exchanged later.

Site Visit by JICA (1)

Outcrops of rhyolite observed along the Arba River, a tributary of the Awash River. Discussions about geology were had with the C/Ps.

Site Visit by JICA (2)

The topographical and geological field survey was carried out in April 2014 at the Study area with Dr. Suzuki, Professor of Okayama University in Japan.

Wonji Sugar Plantation

This large-scale national sugar plantation is located about 10 km south of Adama Town. The photo shows an interview in regard to the general conditions of the plantation.

Metehara Sugar Plantation

This large-scale national sugar plantation is located about 5 km south of Metehara Town. Its area is more than 10,000 ha. The photo shows a well within the plantation.

Observation Well Drilling (1)

Clay balls made of mixed bentonite and straw are thrown into well AWBH-3 to prevent circulation loses and wall collapses between the surface and a depth of 30 m.

Project Photos (4/5)

Observation Well Drilling (2)

Well cleaning at AWBH-11: High-pressured air is sent into the well to discharge the remaining mud after the completion of the well.

Observation Well Drilling (3)

Pumping test at AWBH-1: The volume of pumped groundwater is measured by reading the water level (cm) which overflows the triangular notch tank.

Sampling for Water Quality Test (1)

Water for quality testing was sampled in existing wells, springs, river water, lake water, and so on. The water quality was classified by analysis. The photo shows the sampling of a deep well in East Shewa

Sampling for Water Quality Test (2)

The photo shows the sampling of spring water at the west side of Lake Beseka. The results of analysis of the spring flowing into Lake Besaka are different from that of other springs.

Sampling for Water Quality Test (3)

Water quality sampling was undertaken in the irrigation farm. The result shows the similar characteristic as south shore of Lake Beseka with high HCO_3 which caused by the vegetation.

Discussion of Progress Report 2

Discussion of P/R2 was held on 24th July 2014 attended by the C/P from Ministry of Water, Irrigation and Energy and Oromia Region. The M/M was exchanged later.

Project Photos (5/5)

GIS Workshop

GIS Workshop was held on 30th January 2015 at MoWIE. The theme was about the outline of GIS database for groundwater resources assessment.

Tone Spring

Tone spring is located at the southwest of Lake Beseka. The discharge volume could not be measured since it is submerged though the spring can be observed.

Environmental and Social Consideration

Situation during an interview at Department of Education at Woreda Office in Mojo. The information/data related to water fetching situation enrollment rate was collected.

Discussion of Interim Report

Discussion of IT/R was held on 11th July 2015. The contents have been discussed with the Deputy Minister of MoWIE. The M/M was exchanged later.

Technology Transfer Seminar

The Technology Transfer Seminar was held on 27th October 2015. The presentation includes the output, tasks and recommendations. The seminar was attended by C/Ps (MoWIE, EWTI, GSE, OWMEB and AAU) and NGOs.

Discussion of Draft Final Report

Discussion of DF/R was held on 27th October 2015 and the utilization method of this reports after the Project period have been discussed. The M/M was exchanged later.

Chapter 1

Meteorology and Hydrology

1 Meteorology and Hydrology

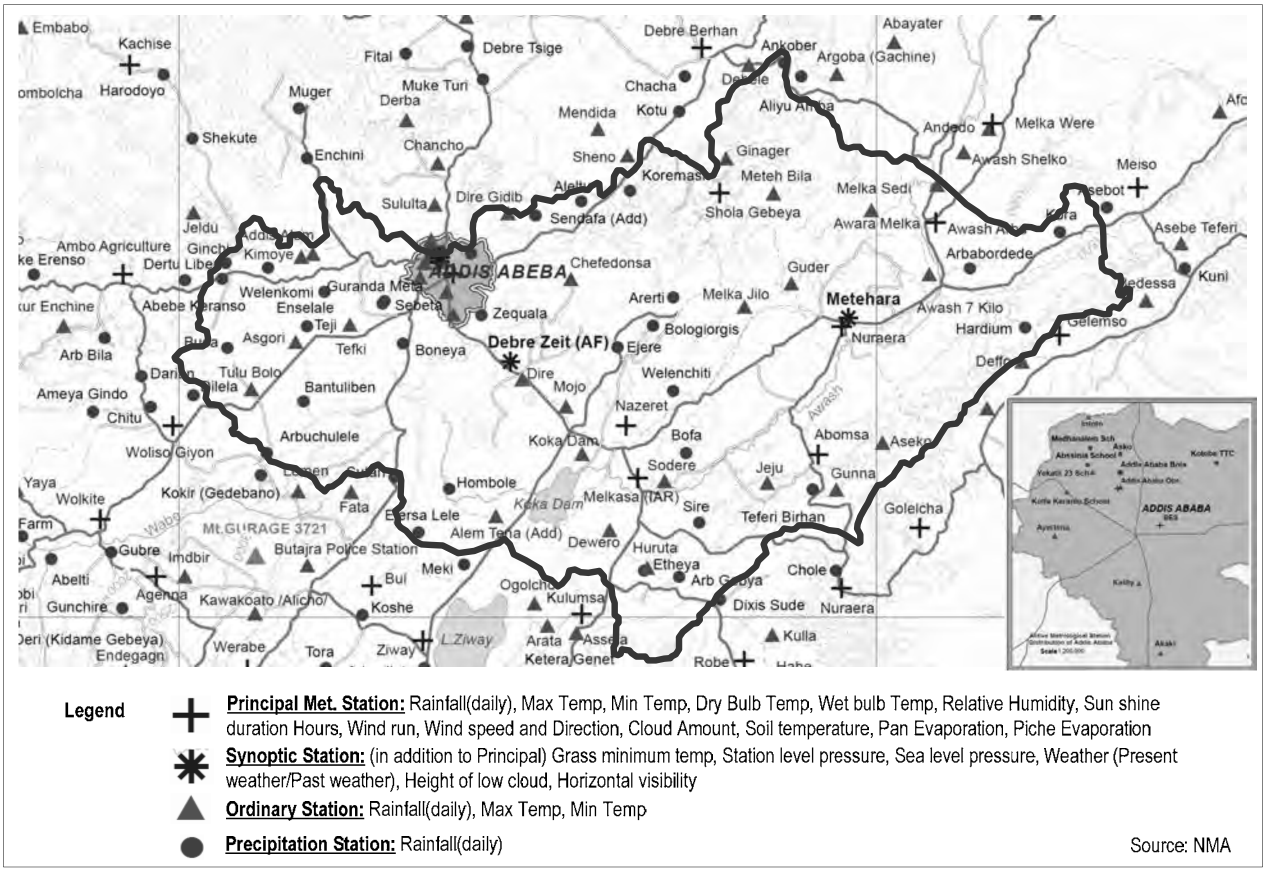
1.1 Review of meteorology data

1.1.1 Meteorological observation network and items

Meteorological stations in Ethiopia, which are managed by the National Meteorological Agency (hereafter referred to as "NMA"), are categorized into the following classes:

- Principal Meteorological Station: For observation of 1) daily rainfall, 2) maximum temperature, 3) minimum temperature, 4) dry bulb temperature, 5) wet bulb temperature, 6) relative humidity, 7) sunshine duration hours, 8) wind run, 9) wind speed/direction, 10) cloud amount, 11) soil temperature, 12) pan evaporation, and 13) Piche evaporation.
- Synoptic Meteorological Station: For observation of 14) grass minimum temperature, 15) station level pressure, 16) sea level pressure, 17) weather (present/past), 18) height of low cloud, and 19) horizontal visibility, in addition to the above-mentioned 13 items observed at Principal stations.
- Ordinary Meteorological Station: For observation of 1) daily rainfall, 2) maximum temperature, and 3) minimum temperature.
- Precipitation Meteorological Station: For observation of daily rainfall.

Location map of the NMA's meteorological stations in and around the Middle Awash River Basin is shown in Figure 1.1.1.



Source: NMA

Figure 1.1.1: Meteorological Stations in and around the Middle Awash River Basin

Number of meteorological stations in the Middle Awash River Basin are tabulated by class (Table 1.1.1).

Table 1.1.1: Number of Meteorological Stations in the Middle Awash River Basin

Class	Number of Stations	Remarks
Principal Met. Station	8	Addis Ababa Obs., BES, Melkasa (IAR), Nazret, Abomsa, Nuraera, Shola Gebeya, Awash Arba
Synoptic Met. Station	3	Addis Ababa Bole, Debre Zeit (AF), Metehara
Ordinary Met. Station	30	
Precipitation Met. Station	33	
Total	74	

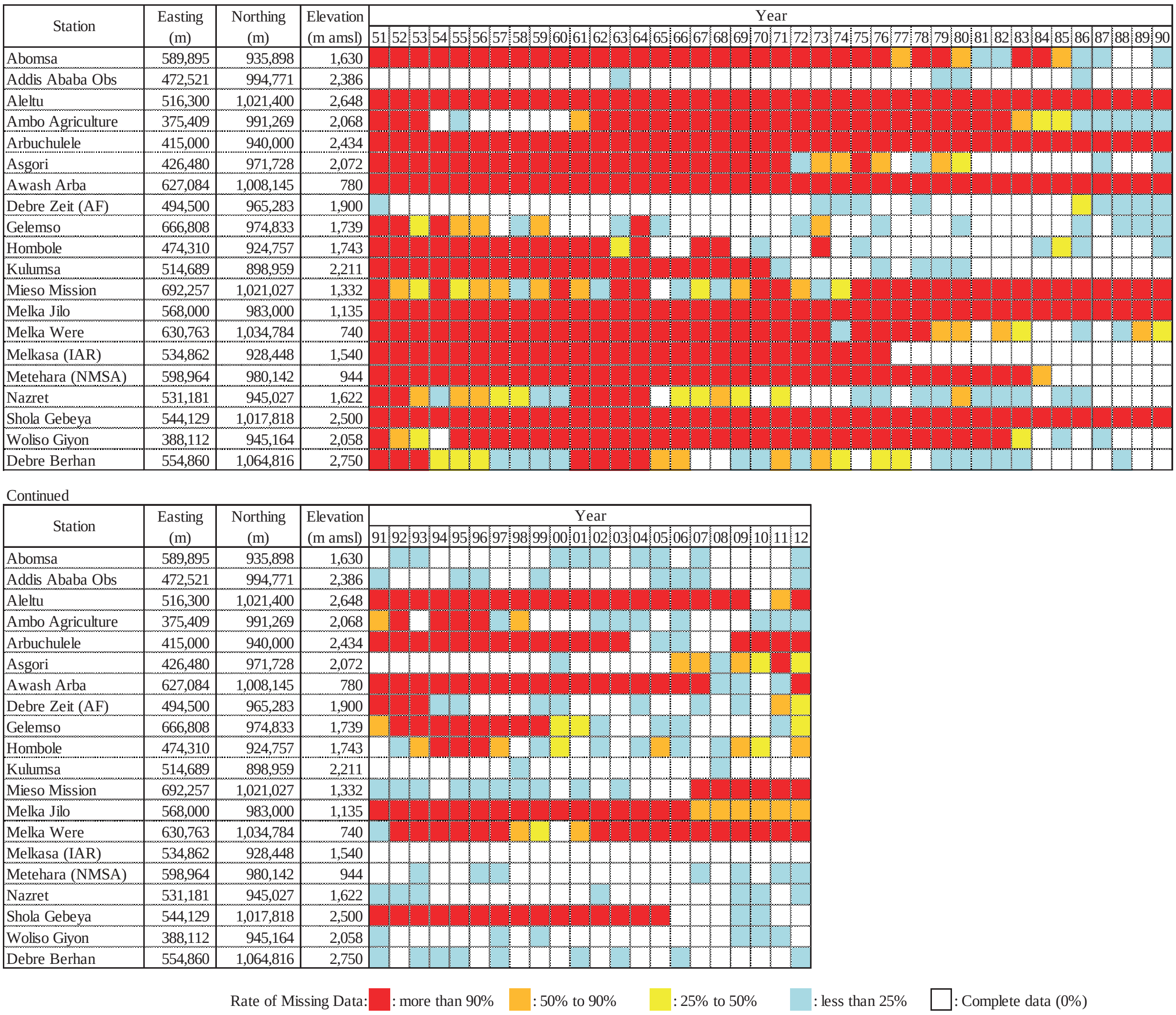
Source: the Project Team, Data: Location data of NMA's observatories

Meteorological data collected from NMA were analyzed as described in the following subsections.

1.1.2 Rainfall

a. Data availability

Daily rainfall data of 62 years (1951–2012) from the following 20 observatories were purchased from NMA. The stations were selected such that the target basin is equally covered. Figure 1.1.2 shows the data availability of each rainfall station.



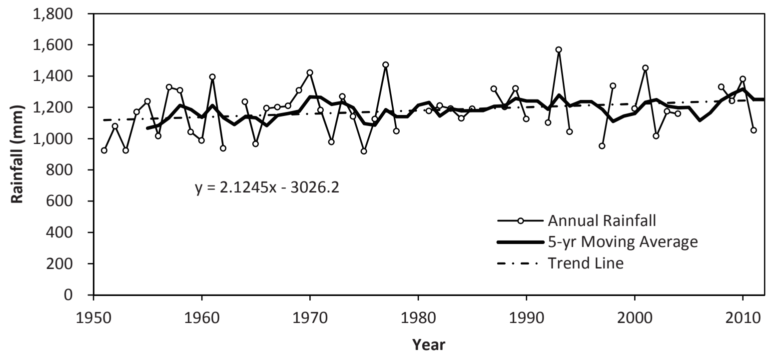
Source: the Project Team, Data: NMA's daily rainfall data

Figure 1.1.2: List of Rainfall Stations with Available Data

Daily rainfall data are available from 1951 at Addis Ababa and Debre Zeit (AF) observatories, while data for only several years are available at Aleltu, Arbuchulele, Awash Arba, and Shola Gebeya observatories.

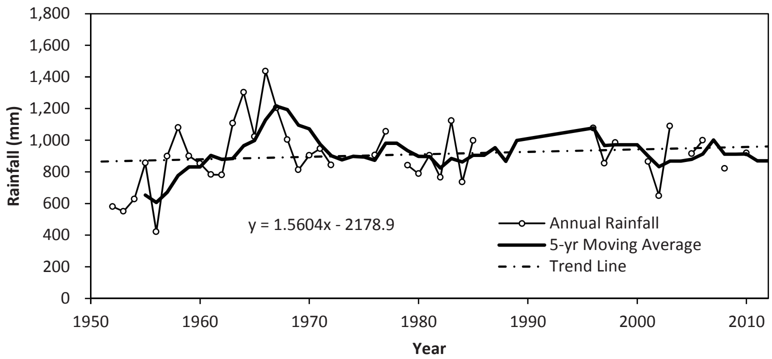
b. Long-term tendency of annual point rainfall

The historical trends of annual rainfall at Addis Ababa, Debre Zeit (AF), and Kulumsa are analyzed as shown in Figure 1.1.3–Figure 1.1.5, respectively.



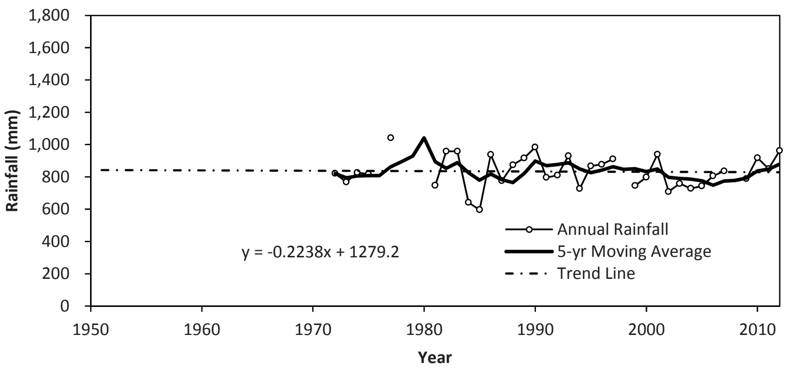
Source: the Project Team, Data: NMA's daily rainfall data

Figure 1.1.3: Historical Trend of Annual Rainfall at Addis Ababa (1951–2011)



Source: the Project Team, Data: NMA's daily rainfall data

Figure 1.1.4: Historical Trend of Annual Rainfall at Debre Zeit (1952–2011)



Source: the Project Team, Data: NMA's daily rainfall data

Figure 1.1.5: Historical Trend of Annual Rainfall at Kulumsa (1972–2012)

The graphs show the annual rainfall for the years without missing data together with 5-years moving average and linear trend line for each observatory. Slight upward trend is observed at Addis Ababa and Debre Zeit, while a downward trend is observed at Kulumsa. Therefore, no significant tendency in annual rainfall in the Middle Awash River Basin is indicated.

c. Spatial rainfall distribution

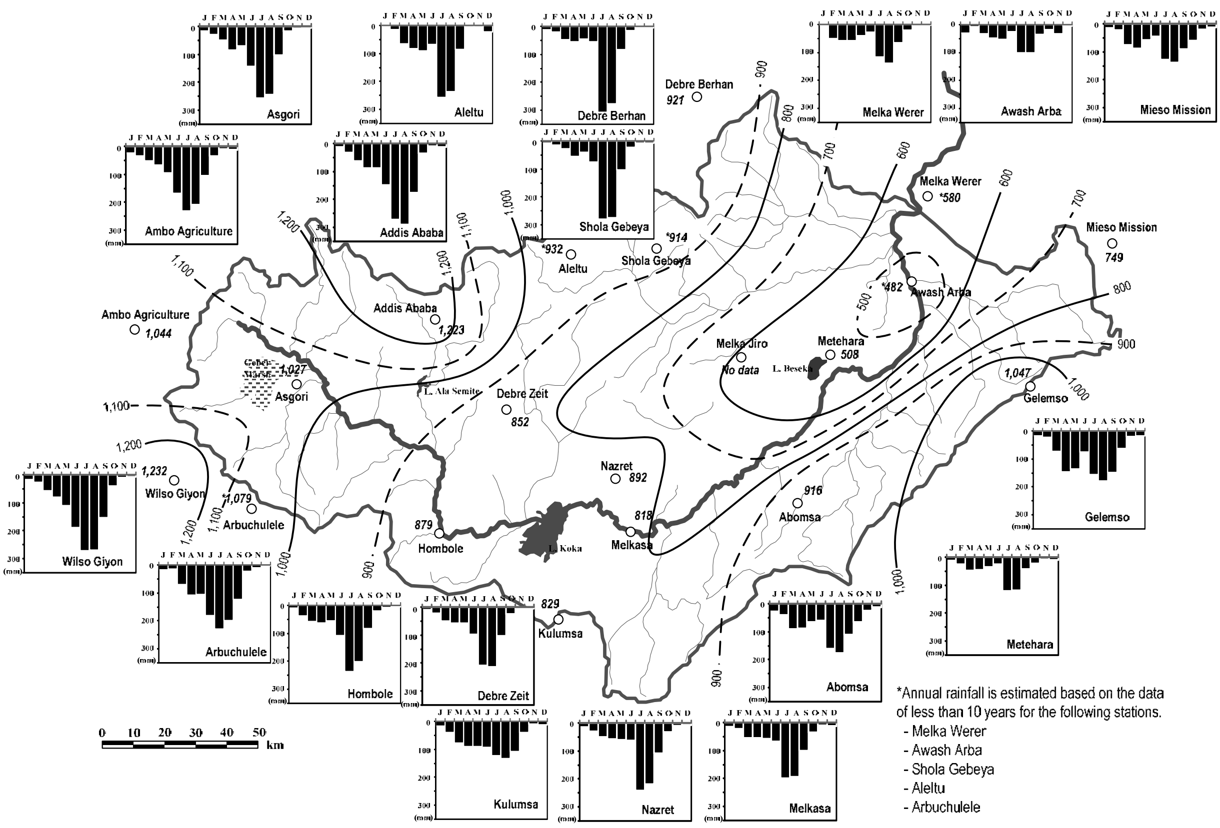
Isohyetal map of the Middle Awash River Basin is generated on the basis of the collected rainfall data. The map is generated in the following procedure:

i) Annual rainfall at each rainfall observatory is calculated.

ii) The calculated annual point rainfall are marked on the map at the location of each observatory.

iii) Lines that show equal amount of annual rainfall are delineated manually referring to the point rainfall.

The generated isohyetal map is shown in Figure 1.1.6.

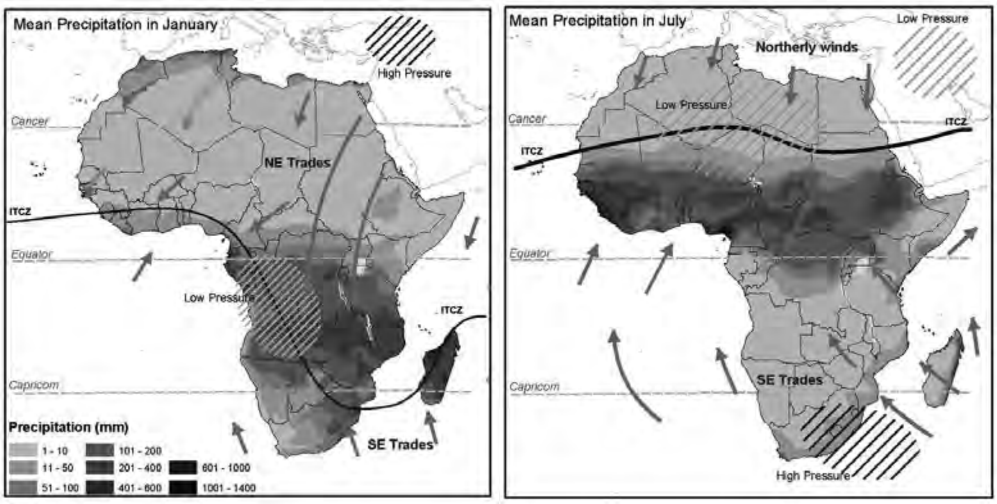


Source: the Project Team, Data: the NMA's daily rainfall data

Figure 1.1.6: Isohyetal Map of the Middle Awash River Basin

The annual rainfall is larger in the northwestern (i.e., upstream) part of the basin. The areas with low annual rainfall are found in the downstream. Annual rainfall in the western and northwestern areas reaches more than 1,000 mm. The annual rainfall in the middle reaches of the Middle Awash around Lake Koka is 800–900 mm. Rainfall of 500 mm or less is observed in the downstream of the Middle Awash from Metehara.

According to Figure 1.1.6, prominent peaks of monthly rainfall can be seen in July and August. Small rainfall peaks are found in March and April in many observatories. The Middle Awash River Basin is located in the climate area characterized by three distinct seasons: Bega (dry season; October–January), Bleg (small rainy season; February–May), and Kiremt (main rainy season; June–September). The rainfall in the area is largely influenced by the position of the Intertropical Convergence Zone (hereafter referred to as "ITCZ"), which is the zone of atmospheric depression formed near equator and shifts north and south in accordance with apparent position of the sun with respect to the earth. The Middle Awash River Basin area experiences the main rainy season when the ITCZ is at its northern-most position around northern Ethiopia to Arabian Peninsula (see Figure 1.1.7).

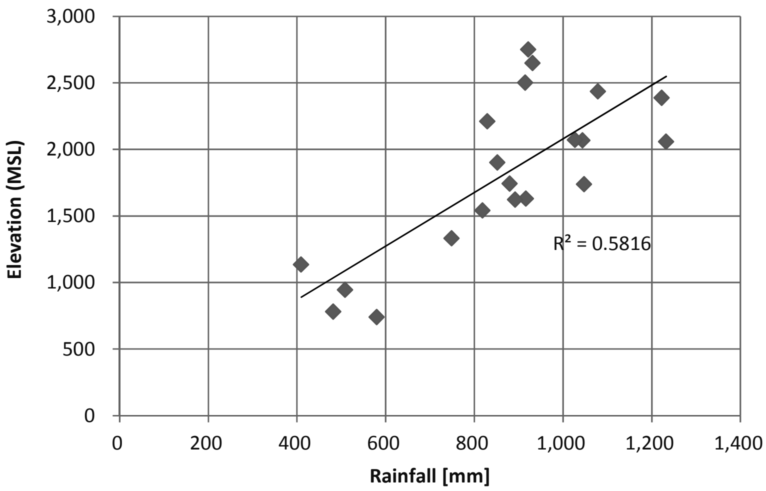


[January] [July]

Source: Grid Africa by United Nations Environment Programme (UNEP)

Figure 1.1.7: Seasonal Drifting of the ITCZ in Africa

The relationship between elevation and annual rainfall at the observatories is plotted as in Figure 1.1.8.



Source: the Project Team, Data: NMA's daily rainfall data

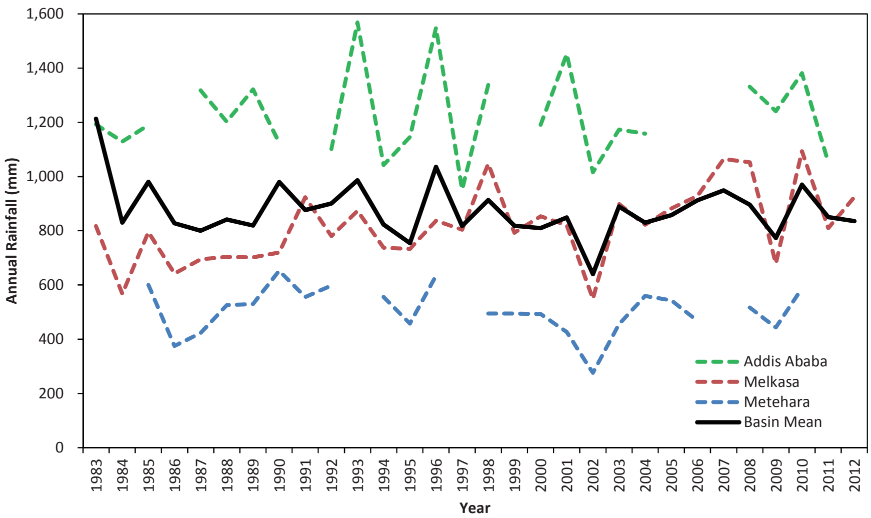
Figure 1.1.8: Relationship between Elevation and Annual Rainfall Amount

Annual rainfall is larger in higher observatory. In the Middle Awash River Basin area, annual rainfall is 400–600 mm in the land with elevation of around EL1,000 m or low. The high lands with elevation of 1,500 m or higher receive annual rainfall of 800–1,200 mm.

d. Basin mean rainfall over the Middle Awash River Basin

The annual mean rainfall over the Middle Awash River Basin was calculated by the Thiessen method. The method uses a graphical technique to calculate station weights based on the relative areas of each measurement station in the Thiessen polygon network. The individual weights are multiplied by the station's point rainfall and the values are summed to obtain the areal average rainfall. The Thiessen polygon network can be generated by connecting intersection points of mediators of triangular network of rainfall observatories.

Historical trend of the annual mean rainfall over the Middle Awash River Basin for current 30 years (1983–2012) is depicted in Figure 1.1.9 together with the annual rainfall data at three representative rainfall stations, i.e., Addis Ababa, Melkasa, and Metehara, for upstream, middle-reaches, and downstream areas, respectively.



Source: the Project Team, Data: NMA's daily rainfall data

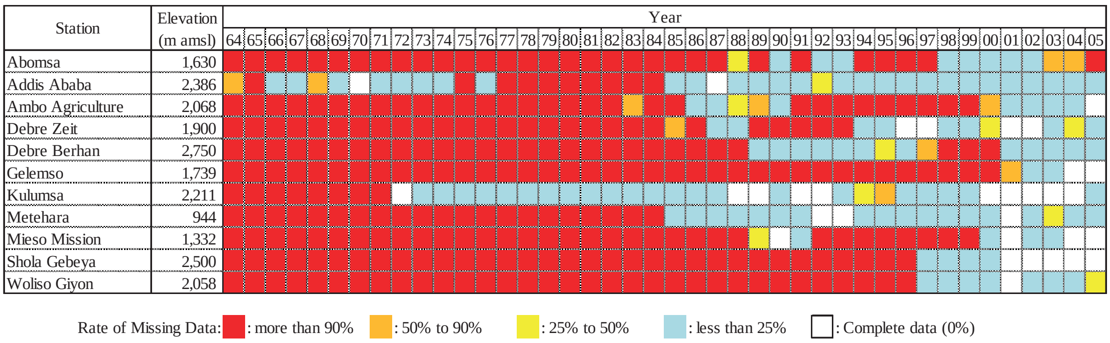
Figure 1.1.9: Historical Trend of Annual Rainfall in the Middle Awash River Basin

The average annual mean rainfall at the Middle Awash River Basin for the period 1983–2012 is 876 mm, while the average annual point rainfall at Addis Ababa, Melkasa, and Metehara is 1,283 mm, 818 mm, and 508 mm, respectively.

1.1.3 Evaporation

a. Data availability

Daily evaporation (Piche) data is collected from NMA. The data for the following 11 observatories are available in hand-written format with plenty of missing data.



Note: Locations of the above observatories are shown in Figure 1.1.6.
Source: the Project Team, Data: NMA's daily evaporation data

Figure 1.1.10: List of Evaporation Observatories with Available Data

b. Estimation of monthly mean evaporation

Monthly evaporation data are estimated on the basis of the daily evaporation data through averaging the total evaporation for the months without missing data. For example, in an observatory, if the complete data for the month of January is available in 1998, 2000, and 2005, the monthly mean evaporation at this observatory is estimated as the simple average of the total evaporation in January for those 3 years.

The estimated monthly mean evaporation data at the 11 observatories are shown in Table 1.1.2.

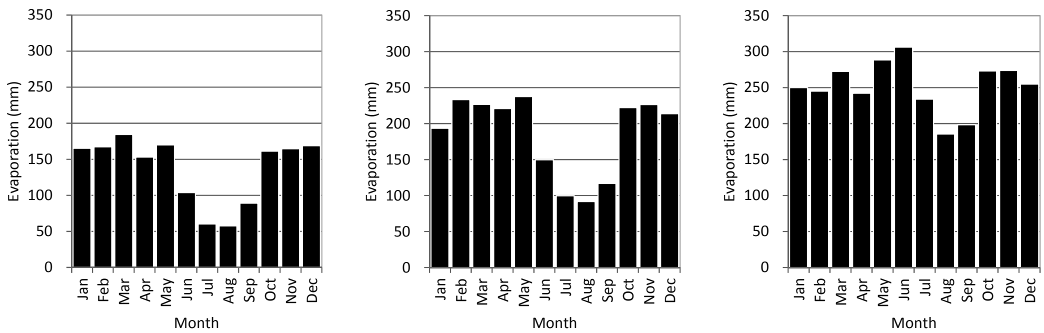
Table 1.1.2: Monthly Mean Evaporation at 11 Observatories

Unit: mm

	Abomsa	Addis Ababa	Ambo Agriculture	Debre Zeit	Debre Berhan	Gelemso	Kulumsa	Metehara	Mieso Mission	Shola Gebeya	Woliso Giyon
Elevation (m amsl)	1,630	2,386	2,068	1,900	2,750	1,739	2,211	944	1,332	2,500	2,058
Jan	190	165	217	193	153	244	200	250	204	152	260
Feb	203	167	229	233	173	288	195	245	215	202	290
Mar	226	184	229	227	163	242	207	272	222	192	259
Apr	232	153	195	221	147	180	192	242	222	194	245
May	303	170	185	238	193	150	197	288	289	253	177
Jun	298	104	83	150	163	139	147	306	309	174	80
Jul	224	61	50	100	68	131	115	234	267	78	51
Aug	163	58	47	92	56	116	96	185	222	64	51
Sep	144	89	62	117	85	108	93	198	176	104	76
Oct	184	161	161	222	127	162	203	273	242	159	178
Nov	205	165	193	226	143	237	217	274	228	164	265
Dec	210	169	216	214	151	244	207	255	197	160	306
Total	2,585	1,646	1,867	2,232	1,622	2,240	2,069	3,023	2,794	1,895	2,239

Note: Locations of the above observatories are shown in Figure 1.1.6.
Source: the Project Team, Data: NMA's daily evaporation data

The annual evaporation varies between 1,622 mm at Debre Berhan (outside the Awash but adjoining) and 3,023 mm at Metehara. Monthly evaporation at three observatories, i.e., Addis Ababa (EL 2,386 m), Debre Zeit (EL 1,900 m), and Metehara (EL 944 m), is graphically shown in Figure 2.11.



Addis Ababa Debre Zeit Metehara

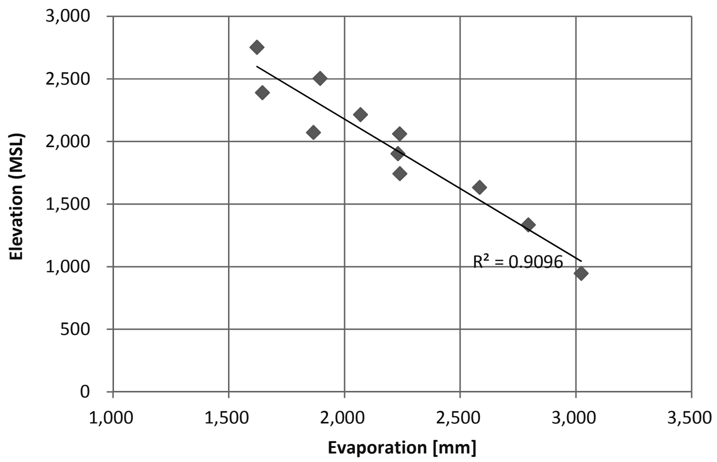
Source: the Project Team, Data: NMA's daily evaporation data

Figure 1.1.11: Monthly Evaporation at Three Observatories

Evaporation shows its minimal value in the main rainy season, July to September. There is no dominant peak of monthly evaporation and the amount is constantly high during dry and minor rainy seasons.

c. Relationship between elevation and evaporation

The relationship between elevation and annual evaporation is plotted on the graph as shown in Figure 1.1.12. Clear correlation is observed between elevation and potential evaporation.



Source: the Project Team, Data: NMA's daily evaporation data

Figure 1.1.12: Relationship between Elevation and Annual Evaporation

d. Comparison between rainfall and evaporation

Annual rainfall and evaporation are compared for 11 observatories as shown in Table 1.1.3. The table shows high potential of evaporation in the target area.

Table 1.1.3: Comparison between Annual Rainfall and Evaporation

Meteorological Station	Elevation (m amsl)	Annual Rainfall (mm)	Annual Evaporation (mm)	Ratio (R/E)	Classification*
Abomsa	1,630	916	2,585	0.35	Semi-arid
Addis Ababa Obs	2,386	1,223	1,646	0.74	Sub-humid
Ambo Agriculture	2,068	1,044	1,867	0.56	Sub-humid
Debre Zeit	1,900	852	2,232	0.38	Semi-arid
Debre Berhan	2,750	921	1,622	0.57	Sub-humid
Gelemso	1,739	1,047	2,240	0.47	Semi-arid
Kulumsa	2,211	829	2,069	0.40	Semi-arid
Metehara	944	508	3,023	0.17	Arid
Mieso Mission	1,332	749	2,794	0.27	Semi-arid
Shola Gebeya	2,500	914	1,895	0.48	Semi-arid
Woliso Giyon	2,058	1,232	2,239	0.55	Sub-humid
Mean	1,956	930	2,201	0.42	

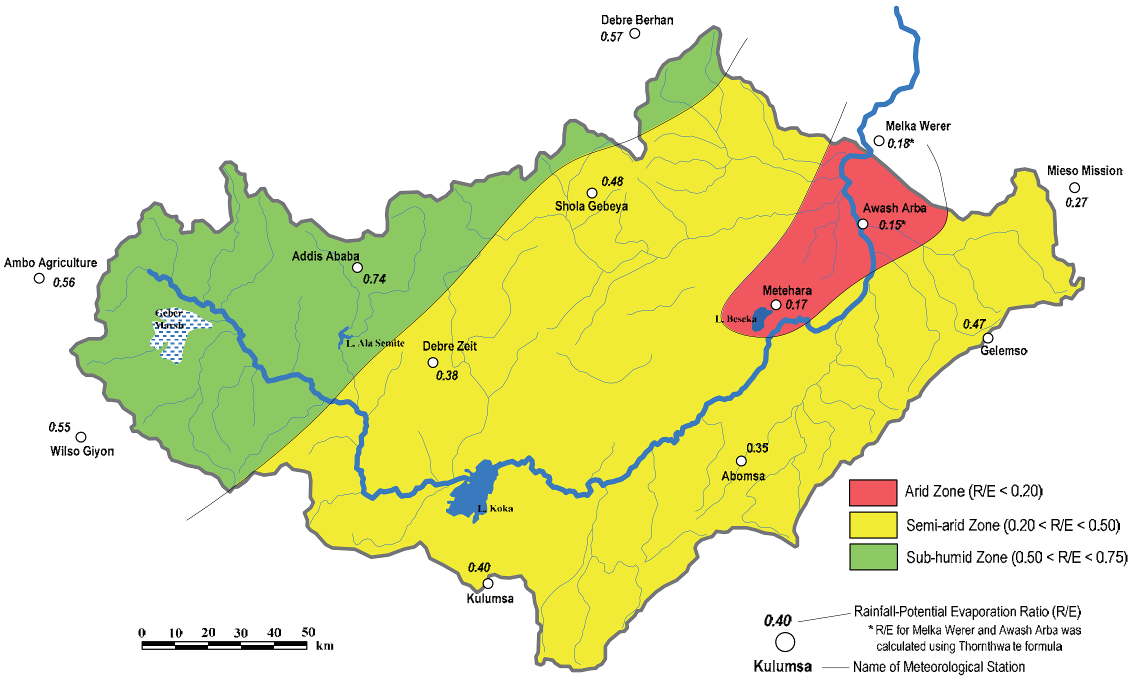
* UNESCO's classification summarized as follows:

R/E < 0.03: Hyper-arid zone
0.03 <R/E < 0.20: Arid zone
0.20 < R/E < 0.50: Semi-arid zone
0.50 < R/E < 0.75: Sub-humid zone

Source: the Project Team, Data: NMA's daily rainfall and evaporation data

As shown in Table 1.1.3, the annual rainfall ranges 17%–74% of the annual evaporation in the Middle Awash area. The ratio is higher in the upstream including Addis Ababa, while that is low in the downstream area such as Metehara.

According to the climatic zone classification by United Nations Educational, Scientific and Cultural Organization (UNESCO), the Middle Awash River Basin is mostly classified into semi-arid zone. Areal distribution of climatic zones is delineated as in Figure 1.1.13.



Source: the Project Team, Data: NMA's daily rainfall and evaporation data

Figure 1.1.13: Climatic Zone Classification in the Middle Awash River Basin

1.1.4 Temperature and other data

a. Collected data

Climatic data of i) minimum/maximum temperature, ii) relative humidity, and iii) sunshine hours are collected on a monthly basis from NMA as shown in Table 1.1.4.

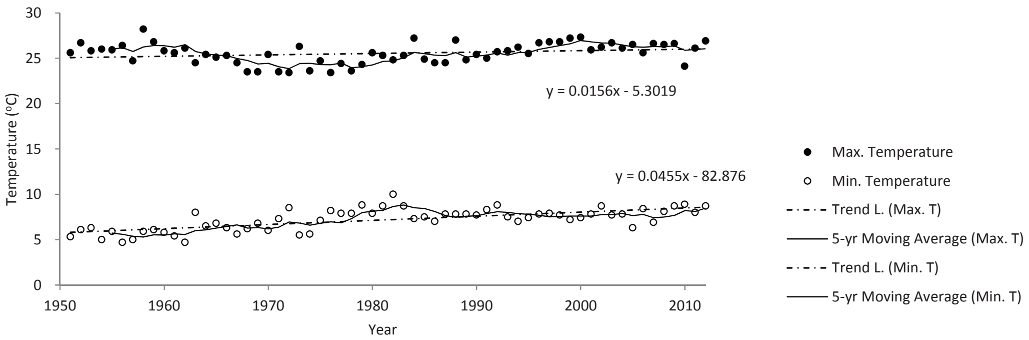
Table 1.1.4: Period of Collection of the Climatic Data

Meteorological Station	Temperature	Relative Humidity	Sunshine Hours
Abomsa	1977–2013	1988–2013	2010–2012
Kulumsa	1971–2013	1972–2013	2010–2013
Gelemso	1986–2013	2010–2013	2010–2012
Addis Ababa Obs	1951–2013	1949–2013	2011–2013
Ambo Agriculture	1954–2013	2010–2013	2010–2013
Debre Berhan	1957–2013	1965–2013	2010–2012
Melkasa (IAR)	1977–2013	1965–2013	1977–2013
Woliso Giyon	1953–2013	2010–2013	2013
Metehara (NMSA)	1984–2013	-	-
Awash Arba	2008–2013	-	-
Debre Zeit (AF)	1951–2012	-	-
Meiso Mission	1952–2006	-	-
Melka Were	1974–2001	-	-
Shola Gebeya	2006–2013	-	-

Source: the Project Team, Data: NMA's climatic data

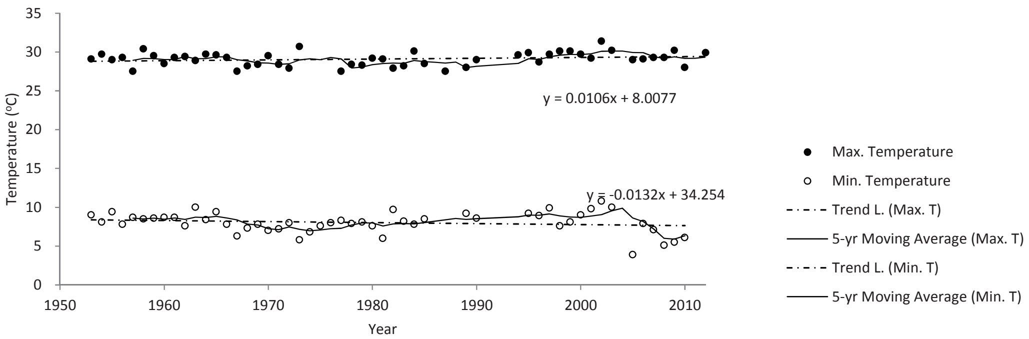
b. Long-term trend of temperature

Figure 1.1.14 and Figure 1.1.15 show the historical trend of maximum and minimum temperatures of Addis Ababa and Debre Zeit, where long-term data are available, together with linear trend line and 5-years moving average.



Source: the Project Team, Data: NMA's climatic data

Figure 1.1.14: Historical Trend of Temperature at Addis Ababa (1951–2012)



Source: the Project Team, Data: NMA's climatic data

Figure 1.1.15: Historical Trend of Temperature at Debre Zeit (1953–2012)

Upward trend is seen for both maximum and minimum temperatures at Addis Ababa. The gradient is larger in minimum temperature. On the other hand, although very slight upward tendency is observed for the maximum temperature at Debre Zeit, the minimum temperature does not show the upward tendency.

c. Summary of climatic data

Maximum and minimum temperatures and relative humidity in and around the Middle Awash River Basin is summarized in Table 1.1.5 and Figure 1.1.16.

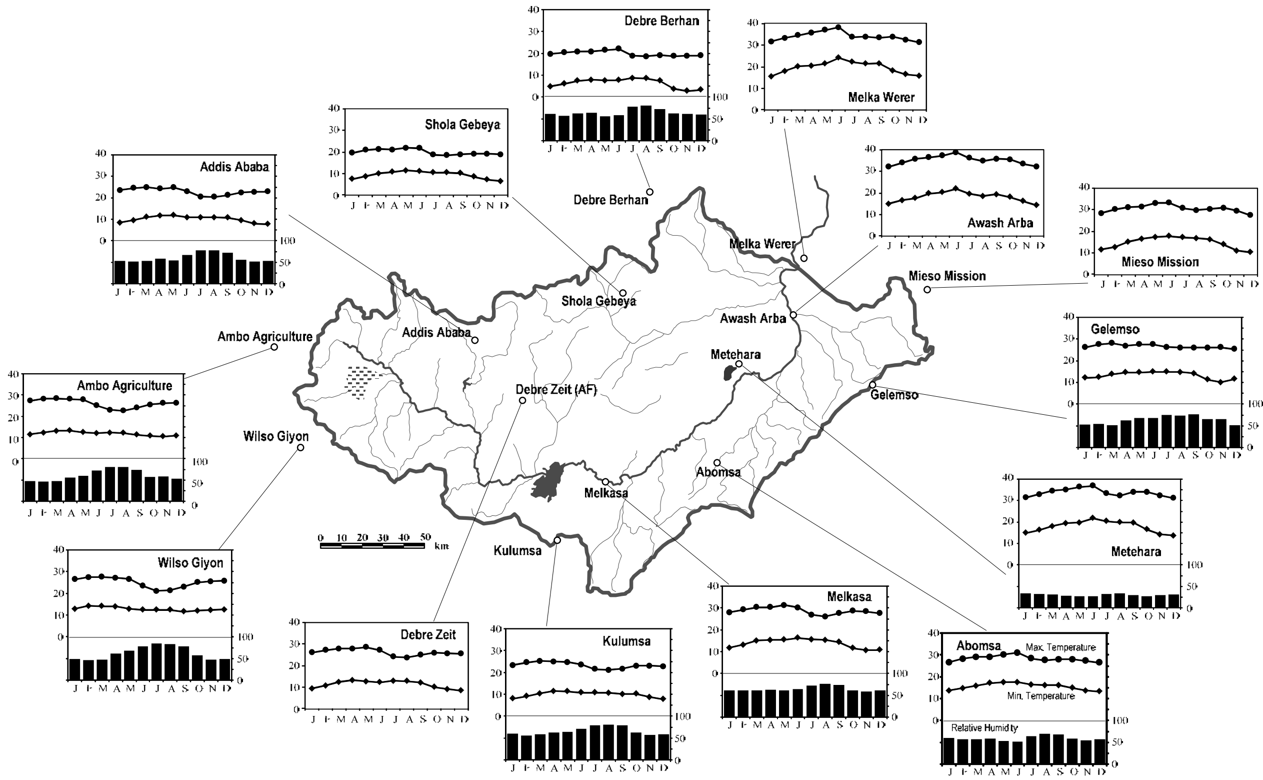
Table 1.1.5: Temperature, Relative Humidity, and Sunshine Hours at Several Stations in and around the Middle Awash River Basin

Station	Elevation (m a.m.s.l)	Max. Temperature (°C)	Min. Temperature (°C)	Annual Mean Temperature (°C)	Annual Mean Relative Humidity (%)	Annual Mean Sunshine Hours (hours/day)
Abomsa	1,630	31.0 (Jun.)	13.2 (Dec.)	21.9	59.3	7.5
Addis Ababa Obs	2,386	24.9 (Mar.)	7.7 (Dec.)	16.5	60.4	6.6
Ambo Agriculture	2,068	28.4 (Mar.)	10.5 (Nov.)	18.9	61.2	6.4
Awash Arba	780	38.9 (Jun.)	14.3 (Dec.)	26.8	-	-
Debre Berhan	2,750	22.0 (Jun.)	2.8 (Nov.)	13.1	64.7	-
Debre Zeit	1,900	28.6 (May)	8.6 (Dec.)	18.9	-	-
Gelemso	1,739	28.1 (Mar.)	10.0 (Nov.)	20.0	64.0	6.7
Kulumsa	2,211	25.2 (Mar.)	7.8 (Dec.)	16.6	65.8	7.0
Melka Werer	740	38.1 (Jun.)	15.3 (Jan.)	26.7	-	-
Melkasa	1,540	31.2 (May)	10.6 (Nov.)	21.2	64.8	8.4

Station	Elevation (m a.m.s.l)	Max. Temperature (°C)	Min. Temperature (°C)	Annual Mean Temperature (°C)	Annual Mean Relative Humidity (%)	Annual Mean Sunshine Hours (hours/day)
Metehara	944	36.9 (Jun.)	13.6 (Dec.)	25.8	30.4	8.5
Mieso Mission	1,332	33.3 (Jun.)	10.5 (Dec.)	22.7	-	-
Shola Gebeya	2,500	22.0 (May)	6.5 (Dec.)	14.7	-	-
Wilso Giyon	2,058	27.6 (Mar.)	11.7 (Sep.)	18.9	62.3	-

-: Data is not available or has not been collected.

Source: the Project Team, Data: NMA's climatic data



Source: the Project Team, Data: NMA's climatic data

Figure 1.1.16: Monthly Temperature and Relative Humidity at Several Stations in and around the Middle Awash River Basin

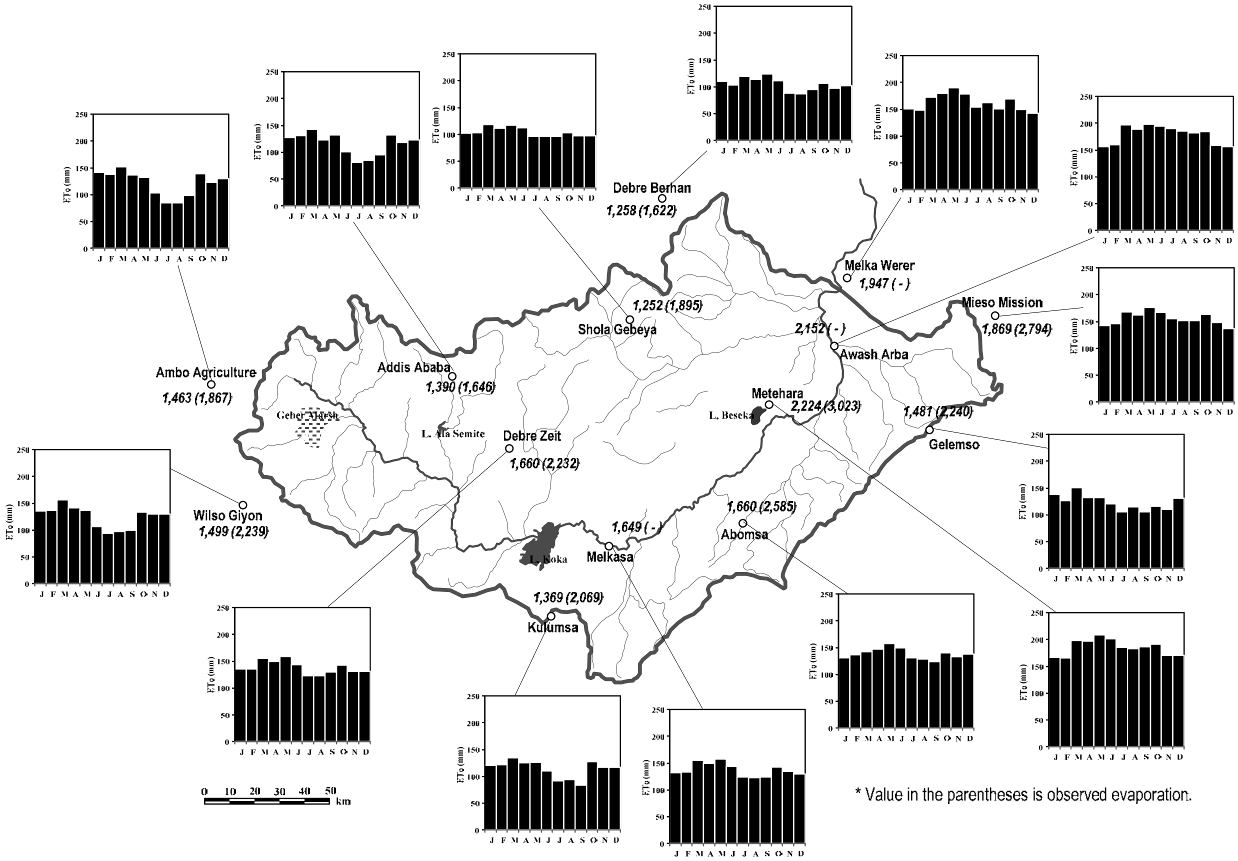
Maximum temperature is observed in the late small rainy season or in the beginning of the main rainy season, i.e., from March to June, at every observatory. In the main rainy season, although the maximum temperature reduces, the minimum temperature is higher. The fluctuation of temperature is, therefore, small in the main rainy season. The maximum temperature reaches more than 36 °C at the stations of downstream regions such as Awash Arba, Melka Werer, and Metehara. The temperature drops less than 10 °C in the high lands such as Addis Ababa, Debre Zeit, Kulumsa, and Shola Gebeya.

In terms of relative humidity, the peak is observed in the main rainy season and annual mean value ranges 60%–65% except for the points in dry regions such as Metehara, where annual mean relative humidity is only 30%.

d. Estimation of reference evapotranspiration at the observatories

Reference evapotranspiration (ETo) is the basic information to estimate ETo from the basin. Although it cannot be measured directly, several estimation methods are proposed. Among them, Food and Agriculture Organization of the United Nations (FAO) recommends Penman–Monteith method[1] as the sole standard method and is widely applied worldwide.

The FAO Penman–Monteith method requires radiation, air temperature, air humidity, and wind speed data. Since the method allows us to estimate ETo even in the case of missing climatic data, the estimation is made applying the collected climatic data. The result is shown in Figure 1.1.17.



Source: the Project Team, Data: NMA's climatic data

Figure 1.1.17: Monthly Reference Evapotranspiration (ETo) in and around the Middle Awash River Basin

As seen in this figure, ETo varies between 1,252 mm/year at Shola Gebeya and 2,224 mm/year at Metehara. ETo in and around the Middle Awash River Basin is corresponding to 65%–80% of evaporation observed by NMA (see section 1.1.3 also).

1.2 Review of hydrology data

1.2.1 Hydrological stations in the middle Awash River Basin

Following table shows the location of hydrological stations managed by MoWIE as of 2013:

[1] http://www.fao.org/docrep/x0490e/x0490e00.htm#Contents

Table 1.2.1: List of Hydrological Stations

SL No.	MAIN CATCHM.	SUB CATCHM.	STN. No.	RIV/LAKE	SITE	LAT.	LON.	UTM North	UTM East	INSTA. DATE	AREA KM2	AVG. ELEV.	REGIONAL OFFICE	REGIONAL GOVERN.
1	AWASH (03)	UPPER (1)	031001	BERGAA	Nr. ADDIS ALEM	9d01'n	38d21'e	996668	428556	15-1-75	248		CEN	OROMIYA
2	AWASH (03)	UPPER (1)	031002	HOLETA	Nr. HOLETA	9d05'n	38d31'e	1004010	446886	16-1-75	119		CEN	OROMIYA
3	AWASH (03)	UPPER (1)	031003	TEJI	Nr. ASGORI	8d47'n	38d20'e	970876	426678	11-75	663	2415	CEN	OROMIYA
4	AWASH (03)	UPPER (1)	031004	AKAKI	@ AKAKI	8d53'n	38d47'e	981872	476177	12-12-80	884	2100	CEN	ADDIS ABABA
5	AWASH (03)	UPPER (1)	031005	L.BISHEFTU	@ DEBRE ZEIT	8d44'n	38d59'e	965283	498167	15-2-81	10		CEN	OROMIYA
6	AWASH (03)	UPPER (1)	031012	AWASH	@ MELKA KUNTIRE	8d42'n	38d36'e	961622	455998	11-62	4456	2332	CEN	OROMYA
7	AWASH (03)	UPPER (1)	031013	AWASH	@ MELKA HOMBOLE	8d23'n	38d47'e	950551	476159	6-62	7656	2300	CEN	OROMYA
8	AWASH (03)	UPPER (1)	031014	MOJO	@ MOJO VILLAGE	8d36'n	39d05'e	950545	509170	8-62	1264	2175	CEN	OROMYA
9	AWASH (03)	UPPER (1)	031015	KELETA	Nr. SIRIE (ARSI)	8d17'n	39d24'e	915560	544050	8-62	747	2800	CEN	OROMYA
10	AWASH (03)	UPPER (1)	031016	AWASH	@ WONJI	8d27'n	39d14'e	933970	525685	3-64	11690		CEN	OROMYA
11	AWASH (03)	UPPER (1)	031017	AWASH	BELOW KOKA DAM	8d28'n	39d10'e	935809	518345	9-61	11219		CEN	OROMYA
12	AWASH (03)	UPPER (1)	031018	HOT SPRING	D.S.OF KOKA	8d27'n	39d12'e	933968	522015	-9-68			CEN	OROMIYA
13	AWASH (03)	UPPER (1)	031019	KESSEM	@ BEKE	9d10'n	39d04'e	1013188	507324	20-3-84	50		CEN	OROMIYA
14	AWASH (03)	UPPER (1)	031020	AWASH	Nr. BELLO	8d51'n	38d25'e	978231	435855	1-5-86	2569		CEN	OROMYA
15	AWASH (03)	UPPER (1)	031021	LIT. AKAKI	D/S GEFERSA DAM	9d02'n	38d42'e	998461	467028	4-8-89	131		CEN	ADDIS ABABA
16	AWASH (03)	UPPER (1)	031022	HORA	@ DEBRE ZEIT	8d46'n	38d59'e	968968	498167	23-8-86	9		CEN	OROMIYA
17	AWASH (03)	UPPER (1)	031023	KURIFTU	Nr. DEBREZEIT	8d46'n	38d58'e	968968	496334	22-8-86	33		CEN	OROMIYA
18	AWASH (03)	UPPER (1)	031025	BISHO (GUDO)	Nr. DEBREZEIT	8d44'n	38d59'e	965283	498167	22-8-86	3		CEN	OROMIYA
19	AWASH (03)	UPPER (1)	031026	MUTINCHA	D/S LEGEDADI DAM	9d03'n	38d55'e	1000291	490842	14-9-89	173		CEN	ADDIS ABABA
20	AWASH (03)	MIDDLE (2)	032001	LAKE BESKA	Nr. METEHARA	8d54'n	39d52'e	983819	595290	29-7-76	596	1176	CEN	OROMIYA
21	AWASH (03)	MIDDLE (2)	032002	ARBA	Nr. ABOMUSSA	8d34'n	39d49'e	946955	589872	4-23-82	140	2329	CEN	OROMIYA
22	AWASH (03)	MIDDLE (2)	032003	AWASH	@ METAHARA	8d51'n	39d51'e	978287	593470	6-62	16417		CEN	OROMYA
23	AWASH (03)	MIDDLE (2)	032004	AWASH	@ AWASH STATION	8d59'n	40d11'e	993130	630082	6-62	19111		EAS	AFAR
24	AWASH (03)	MIDDLE (2)	032005	KESSEM	@ AWARA MELKA	9d09'n	39d57'e	1011482	604381	6-62	3113	2131	CEN	AFAR
25	AWASH (03)	MIDDLE (2)	032009	ARBA	@ BORDEDE	9d01'n	40d21'e	996879	648393	4-2-84	72		EAS	OROMIYA
26	AWASH (03)	MIDDLE (2)	032015	AWASH	@ MELKA SEDI	9d12'n	40d07'e	1017063	622679	APR. 82	21520		EAS	AFAR
27	AWASH (03)	MIDDLE (2)	032016	AWASH	@ MELKA WERER.	9d19'n	40d10'e	1029981	628130	SEP. 72	31183		EAS	AFAR
28	AWASH (03)	MIDDLE (2)	032017	AWASH	@ NURA HERA	8d32'n	39d35'e	943223	564199	JUNE 75	14173		CEN	OROMYA
29	AWASH (03)			AKAKI	Nr. ABA SAMUEL	8d45'n	38d43'e	967138	468836		1476		CEN	OROMYA
30	AWASH (03)			LAKE KOKA	Nr. KOKA DAM	8°28'2.63"N	39° 9'19.97"E				9818		CEN	OROMYA
31	AWASH (03)			AWASH	Nr. GINCHI	9d01'n	38d08'e	996718	404740		76		CEN	OROMIYA

Source: MoWIE

The water level is observed 2 times a day by gauge reader. The average of the readings of the day is recorded as the daily water level. According to the interview with the Hydrological Directorate of MoWIE, the reference elevation such as elevation of the zero point of gauge is not surveyed. Therefore, water level data is not managed with the datum of meter above mean sea level. Since this situation often causes following disadvantages, water level data are recommended to be managed in the elevation datum:

- Data consistency may be lost easily when relocation or reinstallation of staff gauges are undertaken.
- Relationship of water level among observatories such as difference an water slope surface, etc. cannot be calculated directly from the data.

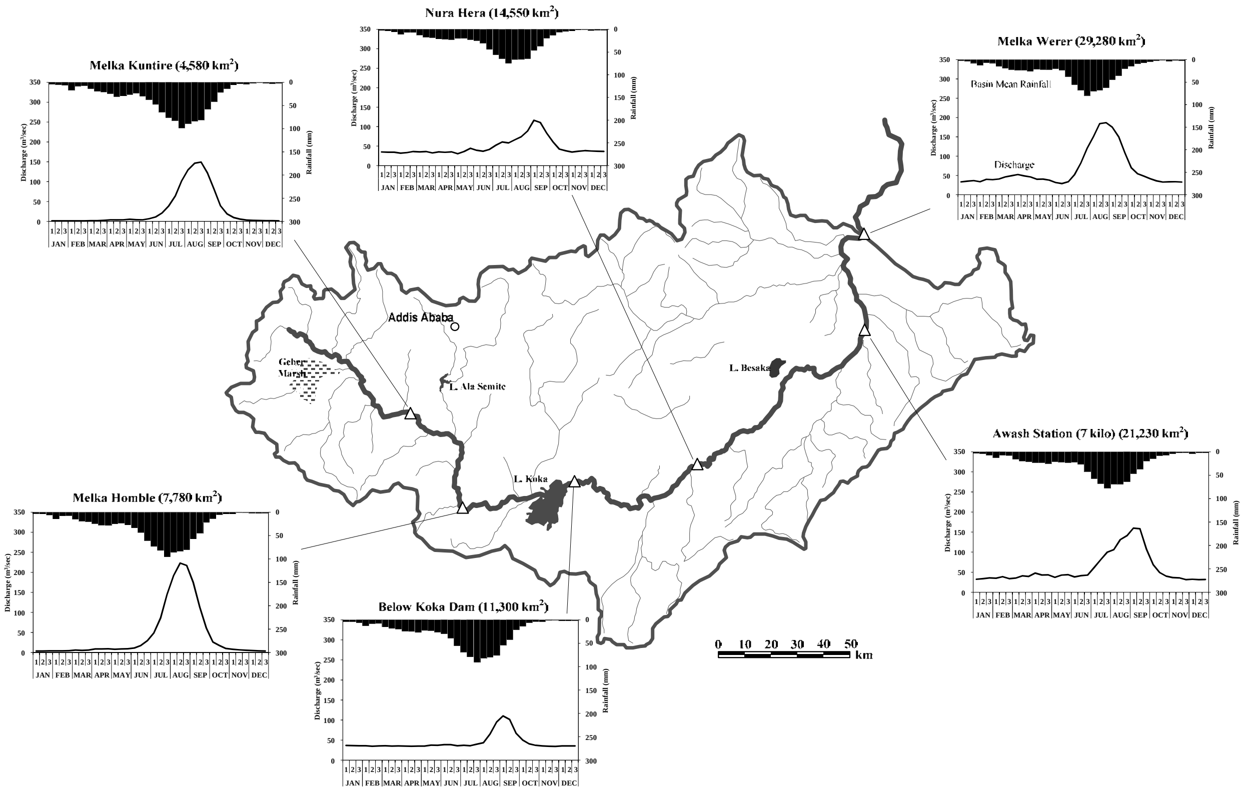
Metehara Water Level Gauging Station

Awash River at Metehara

Daily discharge is estimated applying discharge rating curve which is used to calculate the discharge amount by power function of water level. The rating curve is reviewed and updated only when hydrologists of MoWIE recognizes the need to do so. No routine updating is undertaken. The discharge at the stations is measured once or twice per year on average for the purpose of checking the applicability of existing discharge rating curves, according to the interview with the Directorate.

1.2.2 River flow

Mean 10-day runoff at several water level gauging stations on the Middle Awash is calculated based on the daily discharge data from 1980 to 2009 and presented in Figure 1.2.1 and Table 1.2.2 below:



Source: the Project Team, Data: MoWIE's hydrologic data and NMA's rainfall data

Figure 1.2.1: Mean 10-day Runoff Hydrograph at Major Stations on the Middle Awash

Table 1.2.2: Mean 10-day Runoff at Major Stations on the Middle Awash

			Melka Kuntire	Melka Homble	Below Koka Dam	Nura Hera	Awash Sta.	Melka Werer
Catchment (km²)			4,580	7,780	11,300	14,550	21,230	29,280
Discharge (m^3/sec)	Jan	1	1.5	3.7	36.7	34.9	32.2	33.4
		2	1.6	3.9	36.3	34.4	33.6	35.2
		3	1.4	4.3	36.0	34.3	35.7	36.7
	Feb	1	1.4	4.0	36.1	31.9	34.9	33.9
		2	1.4	4.2	34.7	33.1	38.7	40.0
		3	1.4	4.7	35.4	36.2	33.7	39.1
	Mar	1	1.8	6.0	35.8	35.3	35.3	40.8
		2	2.0	5.1	34.9	36.1	40.8	46.2
		3	2.6	6.2	35.6	32.4	39.3	49.2
	Apr	1	4.0	8.9	35.1	35.2	47.8	52.4
		2	3.7	8.8	34.6	34.0	42.9	48.9
		3	4.0	9.1	35.1	35.1	43.1	46.3
	May	1	5.3	8.0	35.0	30.3	37.2	40.2
		2	4.1	8.9	37.7	36.0	42.6	40.8
		3	4.0	9.0	37.0	44.6	43.8	37.8
	Jun	1	6.9	11.4	38.7	39.2	38.1	31.6
		2	11.2	17.5	38.7	36.8	41.2	28.9
		3	21.7	29.6	36.2	41.6	42.6	33.7
	Jul	1	38.6	49.3	37.1	52.2	61.5	51.9
		2	63.5	85.7	36.2	60.6	81.0	81.9
		3	102.0	144.8	39.9	58.0	99.6	120.5
	Aug	1	129.8	191.7	43.6	66.3	106.1	150.7
		2	146.2	**223.2**	65.2	73.9	131.0	184.3
		3	**149.4**	216.9	94.7	88.9	140.8	**186.8**

			Melka Kuntire	Melka Homble	Below Koka Dam	Nura Hera	Awash Sta.	Melka Werer
	Sep	1	121.5	175.1	**110.2**	**116.2**	**159.7**	174.8
		2	80.9	113.2	101.6	110.8	158.2	150.5
		3	39.2	61.0	66.8	83.6	107.4	108.2
	Oct	1	19.0	26.4	49.9	60.6	69.2	69.6
		2	10.0	17.5	40.6	42.3	49.2	54.5
		3	5.8	9.9	36.9	38.0	40.0	48.2
	Nov	1	3.5	8.3	35.6	34.8	36.4	41.6
		2	2.7	6.6	34.7	36.6	35.8	36.0
		3	2.2	5.8	34.2	38.3	31.4	33.0
	Dec	1	1.9	4.9	35.5	37.5	32.3	33.6
		2	1.8	4.3	35.5	36.8	31.4	33.9
		3	1.6	3.9	35.7	36.4	31.8	33.0
Ann. Mean (m^3/sec)			27.8	41.7	44.0	47.6	58.5	64.1
Height (mm/yr)			191	169	123	103	87	69

Source: the Project Team, Data: MoWIE's hydrologic data

According to the information above:

- Peak runoffs are observed during the period from the middle of August to the beginning of September while peak of rainfall is observed in July and August;
- The Lake Koka releases constant discharge of approximately 35 m^3 per second in dry season;
- Annual runoff height at Melka Werer, the downstream end of the Middle Awash, is 69 mm, and this is less than 8% of the annual basin mean rainfall of 876 mm (1983 – 2012).

1.3 Hydrological analysis

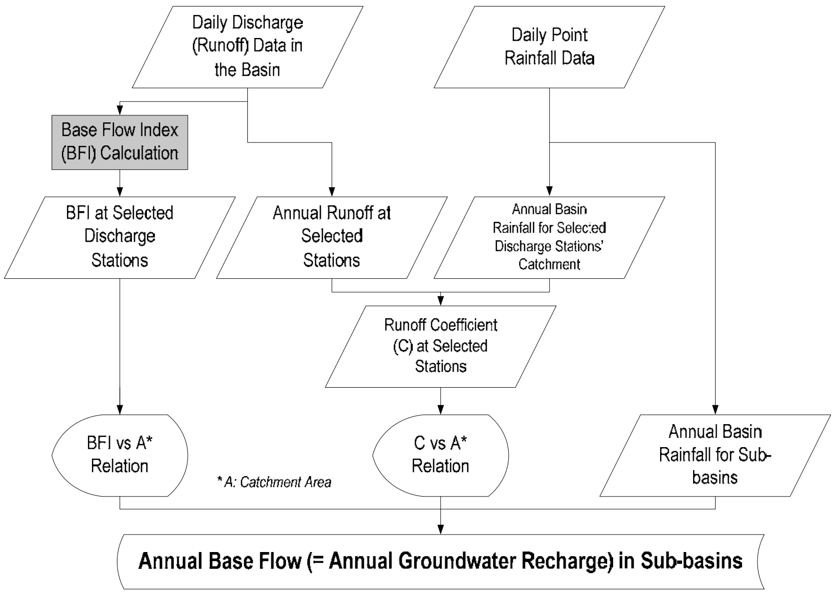
1.3.1 Introduction

a. Purpose of the hydrological analysis

One of the main purposes of the hydrological analysis project is to evaluate the available groundwater resources in the Middle Awash River Basin and formulate a groundwater development plan based on the evaluation. The hydrological analysis is to estimate annual groundwater recharge in the Middle Awash River Basin. In this section, groundwater recharge, which is equivalent to available groundwater resources, is estimated using general relationship between river runoff and groundwater recharge, and other relevant data/information.

b. Procedure

The analysis is undertaken through the procedure shown in Figure 1.3.1.



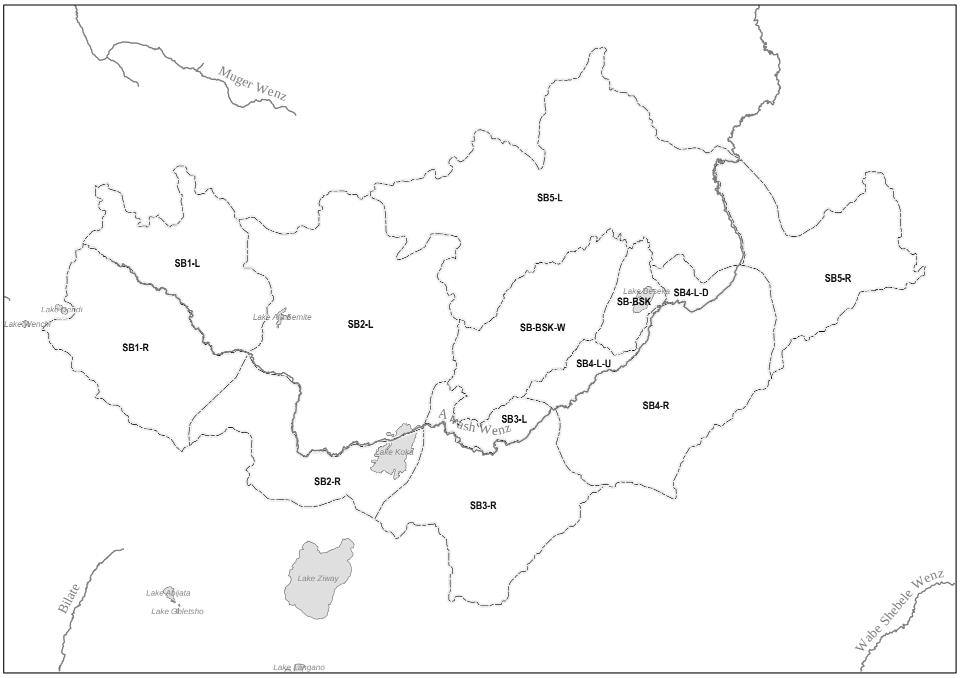
Source: the Project Team, Data: Result of hydrology survey in this Project

Figure 1.3.1: Procedure of the Hydrological Analysis

First, river flow at selected discharge stations in the Middle Awash River Basin is analyzed to obtain base flow amount (or index), which is considered to be equivalent to groundwater recharge. The relationship between base flow amount and catchment area is then analyzed. Second, total river runoff at the selected discharge stations is compared with the stations' basin mean rainfall amount to analyze the relationship between runoff coefficient and catchment area. Further, the groundwater recharge in the sub-basins is estimated by applying the relationships analyzed above.

c. Sub-basins

The Middle Awash River Basin is divided into 13 sub-basins as shown in Figure 1.3.2.



Source: the Project Team, Data: Result of hydrology survey in this Project

Figure 1.3.2: Basin Division for Groundwater Recharge Estimation

Basic concepts based on which the basin is divided are as follows:

- The basin will be divided at existing stream flow gauging station (hereafter referred to as "SFGS") or water level gauging station sites;
- The basin will be divided by the Awash River, namely the left and right bank sides;
- Smaller sub-basins will be extracted for Lake Beseka and adjacent area.

Outlines of the sub-basins are tabulated below. As seen, the catchment areas of sub-basins vary from 310 km^2 to 5,710 km^2:

Table 1.3.1: Summary of Sub-basins

No	Name	Outlet	Area [km^2]	Description
1	SB1-L	Awash	2,068	Catchment of the left bank side of the Awash upstream "Melka Kuntire" SFGS (stream flow gauging station).
2	SB1-R	Awash	2,508	Catchment of the right bank side of the Awash upstream "Melka Kuntire" SFGS.
3	SB2-L	Awash	4,860	Catchment of the left bank side of the Awash between "Below Koka Dam" and "Melka Kuntire" SFGSs
4	SB2-R	Awash	1,859	Catchment of the right bank side of the Awash between "Below Koka Dam" and "Melka Kuntire" SFGSs
5	SB3-L	Awash	508	Catchment of the left bank side of the Awash between "Nura Hera" and "Below Koka Dam" SFGSs
6	SB3-R	Awash	2,743	Catchment of the right bank side of the Awash between "Nura Hera" and "Below Koka Dam" SFGSs
7	SB4-L-U	Awash	435	Catchment of the left bank side of the Awash between the bridge on the Awash at the entrance of Metehara Sugar Plantation and "Nura Hera" SFGS
8	SB4-L-D	Awash	312	Catchment of the left bank side of the Awash between "Awash Station" SFGS and the bridge on the Awash at the entrance of Metehara Sugar Plantation
9	SB4-R	Awash	3,367	Catchment of the right bank side of the Awash between "Awash Station" and "Nura Hera" SFGSs

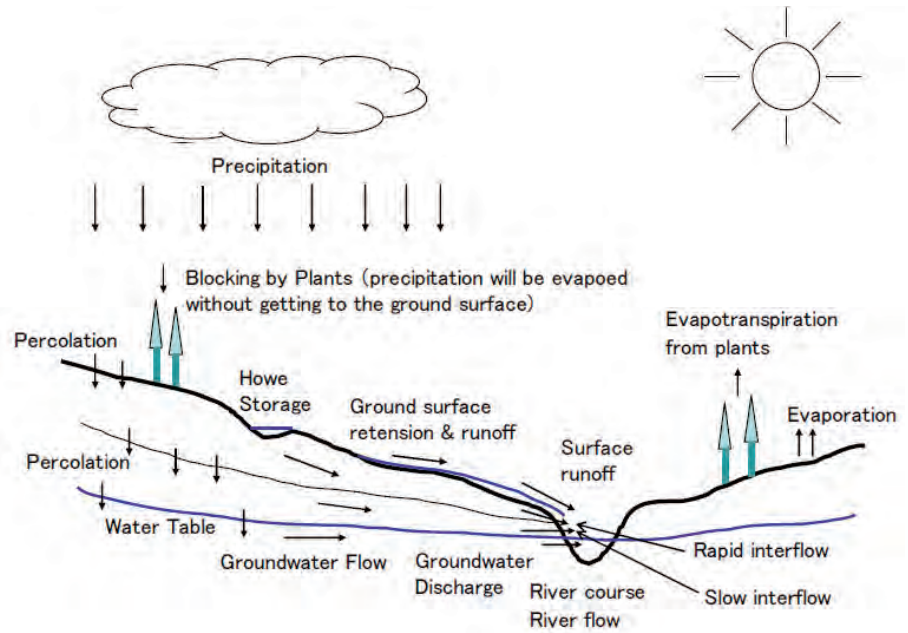
No	Name	Outlet	Area [km²]	Description
10	SB5-L	Awash	5,710	Catchment of the left bank side of the Awash between "Melka Werer" and "Awash Station" SFGSs
11	SB5-R	Awash	2,347	Catchment of the right bank side of the Awash between "Melka Werer" and "Awash Station" SFGSs
12	SB-BSK-W	Depression (no outlet is confirmed topographically)	2,041	Catchment in the western side of the Lake Beseka Catchment
13	SB-BSK	Lake Beseka, Awash (through a Drainage Channel)	532	Catchment of the Lake Beseka
		Total	29,289	

Source: the Project Team, Data: Result of hydrology survey in this Project

1.3.2 River flow analysis

a. Relationship between river flow and groundwater flow

As shown in Figure 1.3.3, the river water is formed by direct runoff due to precipitation and groundwater discharge to the river.



Source: Reference (1)

Figure 1.3.3: Precipitation and Process of River Water Formation

Direct 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 discharges 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 are usually high compared to the surface water level. Thus the groundwater usually flows from higher to lower levels into river streams.

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

In contrast, the velocity of the 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 are replenished by groundwater inflow under no-rain conditions.

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

b. Method of groundwater recharge analysis

There are several methods to directly calculate the groundwater recharge and the 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. Therefore, the groundwater recharge cannot be directly calculated.

On the other hand, the recharge and discharge amounts are more or less equal in a long-term 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 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.

c. Separation of river flow components (BFI calculation)

The ratio of the groundwater component in a river flow is defined as base flow index (hereafter referred to as “BFI”). 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 naturally differ depending on the method employed. In this analysis, the following two methods (programs) were selected since both are considered to be reliable:

Program 1: PART (United States Geological Survey: USGS, 2007)[2]. 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

2 http://water.usgs.gov/ogw/part/

long period of record to obtain an estimate of the mean rate of groundwater discharge.

Program 2: BFI (United States Bureau of Reclamation: USBR, 2013)[3]. This program begins by partitioning the year into N-day periods and determining the minimum flow within each period. These minimum flows are the potential turning points on the base-flow hydrograph. (If the year is not evenly divisible by N, any remaining days will be included in the last period of the year). When several days within one period are tied for the lowest flow, the earliest day will be considered the minimum, except during the last N-day period of each year, when the minimum will be considered to occur on the latest day. To determine the turning points on the base-flow hydrograph, the collection of N-day minimum flows is processed using the following turning-point test:

Given three adjacent N-day minimum flows, Q_0, Q_1, and Q_2,

Q_1 is a turning point IF

$$Q_1 * f <= Q_0 \text{ and } Q_1 * f <= Q_2$$

where, f is a turning-point test factor that must be greater than 0 and should be less than 1.

If Q_1 is zero, it will always be a turning point. If either Q_0 or Q_2 is equal to zero, then the test is only performed against the non-zero value. If both Q_0 and Q_2 are zero, Q_1 cannot be a turning point unless it is zero.

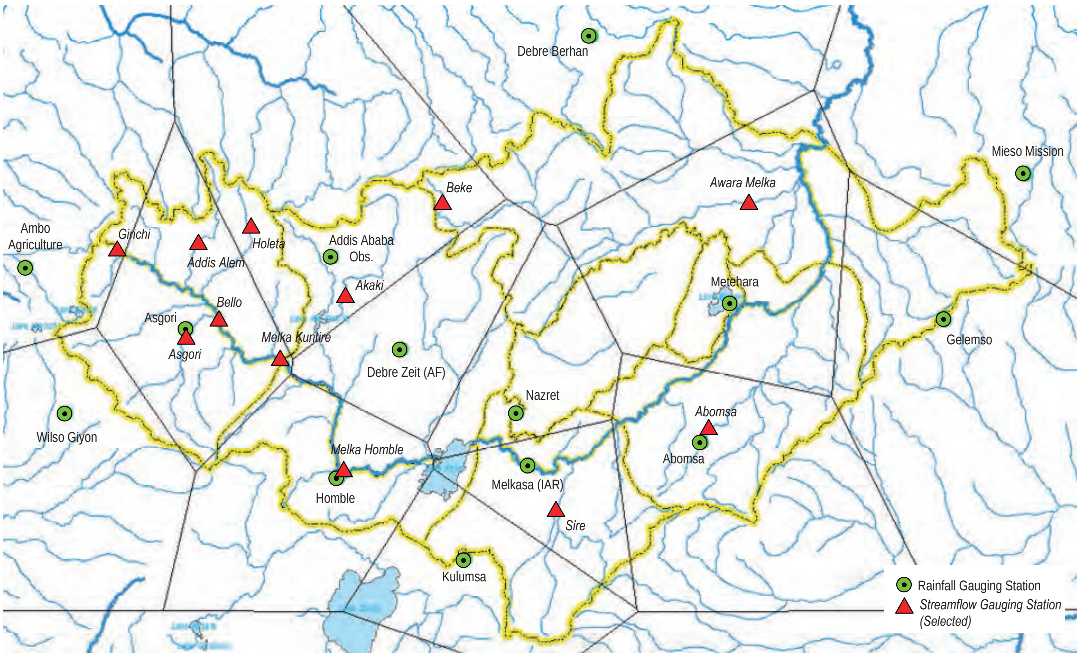
d. Selection of streamflow gauging stations for BFI calculation

Hydrological stations subject to BFI calculation are selected on the basis of the following two criteria:

- The stations shall not be affected by the artificial control.
- The stations shall have time series discharge data of at least 5 years without missing.

Based on the above criteria, following 12 stations are selected for the BFI calculation:

3 http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/



Source: the Project Team, Data: Result of hydrology survey in this Project

Figure 1.3.4: Location Map of Selected Stations for BFI Calculation

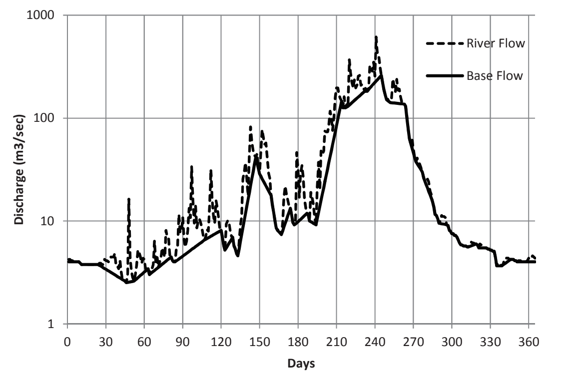
Table 1.3.2: Selected Stations for BFI Calculation

Station Name	River Name	Area (km^2)	Number of Years	Period
Abomsa	Arba	140	5	1995–1999
Addis Alem	Berga	248	18	1984, 1989–1991, 1993–2002, 2004–2007
Akaki	Akaki	884	14	1983–1984, 1986–1992, 2000–2004
Awara Melka	Kesem	3,113	20	1983–1984, 1986–2000, 2003–2004, 2006
Asgori	Teji	663	11	1983–1985, 1987–1991, 1996, 2001, 2007
Beke	Kesem	50	14	1986, 1988–1989, 1993, 1995–1997, 1999–2003, 2005–2006
Bello	Awash	2,569	11	1987–1990, 1992, 1994, 1996–1997, 2000, 2004, 2008
Ginchi	Awash	76	12	1994–1995, 1997, 1999–2007
Holeta	Holeta	119	16	1988, 1991, 1994–2002, 2004–2008
Melka Homble	Awash	7,780	27	1983–2009
Melka Kuntire	Awash	4,580	24	1983–1984, 1986–2005, 2007–2008
Sire	Keleta	747	13	1983–1984, 1985, 1987–1988, 1990–1993, 1995, 1997, 1999–2000

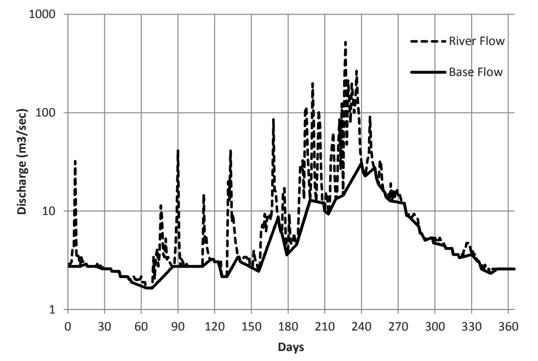
Source: the Project Team, Data: Result of hydrology survey in this Project

e. Example of flow component separation (BFI calculation)

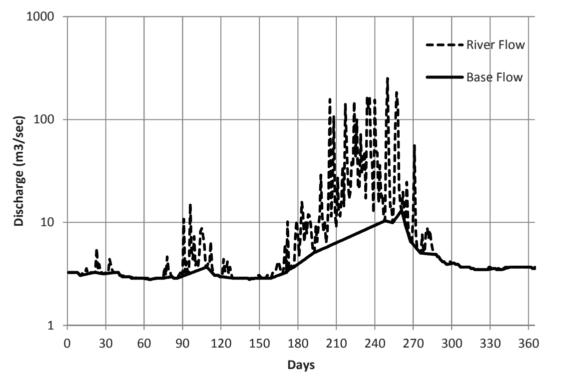
Figure 1.3.5 presents hydrographs showing examples of base flow separation results. The BFI is the proportion of the base flow volume (area below the solid line in the hydrographs) to the river flow volume (area below the dotted line).



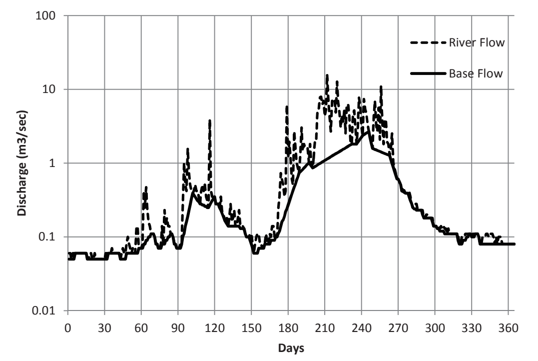
Melka Homble on the Awash River (1983)



Awara Melka on the Kesem River (1996)



Akaki on the Akaki River (2004)



Beke on the Kesem River (2000)

Source: the Project Team, Data: Result of hydrology survey in this Project

Figure 1.3.5: Examples of Base Flow Separation Results

f. Result of BFI calculation

The BFI was calculated using both programs: “PART” and “BFI.” Since results vary considerably by programs and years, the results of the year that is relatively consistent between both programs are adopted for further analysis. Specifically, results that have a difference of 25% or less between “PART” and “BFI” are adopted as reliable BFI. Calculated mean BFI values are shown in Table 1.3.3 together with the duration of the data adopted.

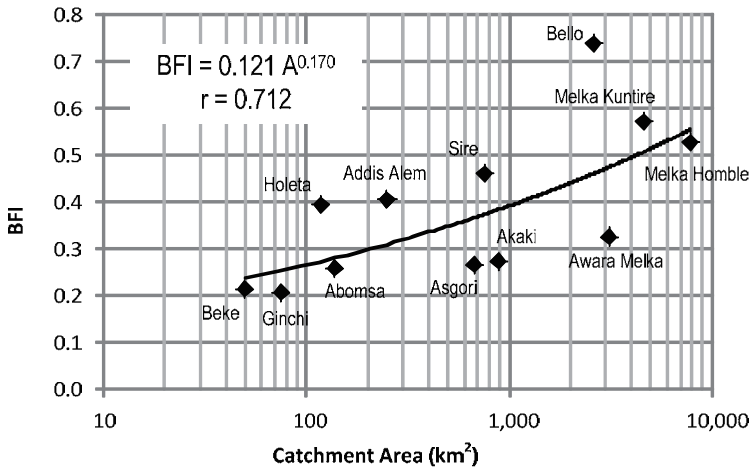
Table 1.3.3: Calculated BFI Values from Flow Separation Analysis

Station Name	River Name	Area (km^2)	PART	BFI	Min	Period Adopted
Abomsa	Arba	140	0.28	0.26	0.26	1995–1996, 1998–1999
Addis Alem	Berga	248	0.40	0.42	0.40	1984, 1989–1991, 1993, 1996, 1998–2000, 2006–2007
Akaki	Akaki	884	0.28	0.32	0.28	1983–1984, 1986–1987, 1990–1992, 2000–2004
Awara Melka	Kesem	3,113	0.33	0.33	0.33	1984, 1986, 1990–1991, 1993, 1995–1997, 1999, 2004
Asgori	Teji	663	0.27	0.27	0.27	1983–1987, 1989
Beke	Kesem	50	0.21	0.25	0.21	1986, 1993, 2000–2001
Bello	Awash	2,569	0.74	0.77	0.74	1987–1990, 1996–1997
Ginchi	Awash	76	0.21	0.21	0.21	1994, 1997, 1999–2007
Holeta	Holeta	119	0.39	0.42	0.39	1988, 1991, 1995–2002, 2004–2008
Melka Homble	Awash	7,780	0.52	0.57	0.52	1983–1984, 1987, 1990–1991, 1993–1994, 1996–2000, 2003, 2005, 2007, 2009
Melka Kuntire	Awash	4,580	0.57	0.60	0.57	1983, 1986–1988, 1990–1991, 1993–1994, 1996, 1999–2002,

Station Name	River Name	Area (km^2)	PART	BFI	Min	Period Adopted
						2004–2005, 2007–2008
Sire	Keleta	747	0.48	0.46	0.46	1983–1985, 1987–1988, 1990–1993, 1995, 1997, 1999–2000

Source: the Project Team, Data: Result of hydrology survey in this Project

The minimum (smaller) BFI value calculated by "PART" and "BFI" programs is considered as the BFI at a gauging station from the conservative view. Figure 1.3.6 shows the calculated BFIs plotted with the catchment area on the x-axis.



Source: the Project Team, Data: Result of hydrology survey in this Project

Figure 1.3.6: Relationship between Catchment Area and BFI Values

The graph shows high correlation (r > 0.70) between catchment area and BFI. According to the figure, the larger the catchment area, the larger is the BFI. This is reasonable considering that water originated from precipitation shall travel longer distance and time in larger basins. This may provide more occasions for runoff to percolate in groundwater domain during its travel.

1.3.3 Water balance analysis

a. Runoff coefficient at selected 12 gauging stations

BFI at 12 hydrological stations in the Middle Awash River Basin is estimated in the subsection above. BFI is the percentage of base flow to the total river runoff as explained. Therefore, the groundwater recharge amount can be quantitatively estimated if the river runoff amount is available.

Runoff coefficient at 12 stations is calculated as the percentage of annual river runoff to annual basin mean rainfall. Annual river runoff can be obtained from the daily discharge record. Annual basin mean rainfall is estimated on the basis of the point rainfall data by applying the Thiessen method (see Figure 1.3.4 for the Thiessen polygons). Table 1.3.4 shows the Thiessen ratio for calculation of basin mean rainfall for the catchments of 12 stations.

Table 1.3.4: Thiessen Ratio for Selected 12 Stations' Catchments

Station Name	River Name	Area (km^2)	Number of Rainfall Stations	Rainfall Station	Thiessen Ratio
Abomsa	Arba	140	1	Abomsa	1.00
Addis Alem	Berga	248	2	Asgori	0.50
				Addis Ababa Obs.	0.50
Akaki	Akaki	884	1	Addis Ababa Obs.	1.00
Awara Melka	Kesem	3,113	5	Metehara	0.34
				Debre Berhan	0.30
				Addis Ababa Obs.	0.13
				Debre Zeit (AF)	0.06
				Nazret	0.17
Beke	Kesem	50	1	Addis Ababa Obs.	1.00
Bello	Awash	2,569	4	Asgori	0.60
				Addis Ababa Obs.	0.17
				Ambo Agriculture	0.16
				Wilso Giyon	0.07
Ginchi	Awash	76	1	Ambo Agriculture	1.00
Holeta	Holeta	119	1	Addis Ababa Obs.	1.00
Melka Homble	Awash	7,780	6	Addis Ababa Obs.	0.27
				Debre Zeit (AF)	0.10
				Homble	0.13
				Asgori	0.40
				Ambo Agriculture	0.05
				Woliso Giyon	0.05
Melka Kuntire	Awash	4,580	5	Asgori	0.66
				Addis Ababa Obs.	0.16
				Ambo Agriculture	0.09
				Woliso Giyon	0.08
				Homble	0.01
Sire	Keleta	747	2	Melkasa	0.33
				Kulumsa	0.67

Source: the Project Team, Data: Result of hydrology survey in this Project

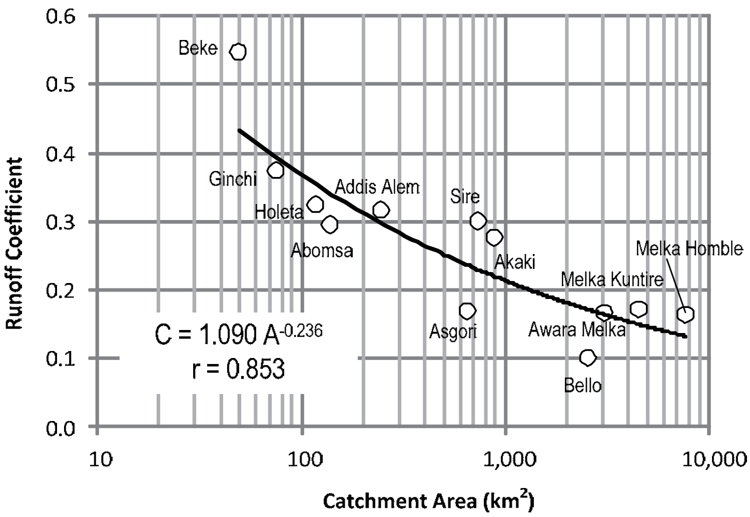
Calculated mean annual rainfall and runoff are shown in Table 1.3.5. Annual runoff ranges between 111 mm/year at Bello and 682 mm/year at Beke, while annual rainfall ranges between 806 mm/year at Sire and 1,249 mm/year at Beke.

Table 1.3.5: Mean Annual Runoff and Rainfall for Selected Stations

Station Name	River Name	Area (km^2)	Runoff (mm/yr)	Rainfall (mm/yr)	Runoff Coefficient	Period
Abomsa	Arba	140	301	1,018	0.295	1995–1999
Addis Alem	Berga	248	357	1,136	0.315	1984, 1989–1991, 1993–2002, 2004–2007
Akaki	Akaki	884	331	1,198	0.276	1983–1984, 1986–1992, 2000–2004
Awara Melka	Kesem	3,113	135	824	0.164	1983–1984, 1986–2000, 2003–2004, 2006
Asgori	Teji	663	189	1,115	0.169	1983–1985, 1987–1991, 1996, 2001, 2007
Beke	Kesem	50	682	1,249	0.546	1986, 1988–1989, 1993, 1995–1997, 1999–2003, 2005–2006
Bello	Awash	2,569	111	1,098	0.101	1987–1990, 1992, 1994, 1996–1997, 2000, 2004, 2008
Ginchi	Awash	76	364	979	0.372	1994–1995, 1997, 1999–2007
Holeta	Holeta	119	393	1,220	0.322	1988, 1991, 1994–2002, 2004–2008
Melka Homble	Awash	7,780	172	1,066	0.162	1983–2009
Melka Kuntire	Awash	4,580	188	1,103	0.171	1983–1984, 1986–2005, 2007–2008
Sire	Keleta	747	242	806	0.300	1983–1984, 1985, 1987–1988, 1990–1993, 1995, 1997, 1999–2000

Source: the Project Team, Data: Result of hydrology survey in this Project

In general, the larger the catchment area, the smaller is the runoff coefficient. This can be said for the Middle Awash River Basin. The relationship between catchment area and runoff coefficient is depicted in Figure 1.3.7.



Source: the Project Team, Data: Result of hydrology survey in this Project

Figure 1.3.7: Relationship between Catchment Area and Runoff Coefficient

The graph shows high correlation (r > 0.85) between catchment area and runoff coefficient.

b. Annual Groundwater Recharge in the Selected 12 Gauging Stations' Catchments

Based on the above, annual groundwater recharge (hereafter referred to as "GWR") can be expressed as follows:

$$GWR = R \cdot C \cdot BFI$$

where, *GWR*: Annual groundwater recharge (mm/year)
R: Annual basin mean rainfall (mm/year)
C: Runoff coefficient (-)
BFI: Base flow index (-)

The annual groundwater recharge at selected 12 gauging stations' catchments is estimated as shown in Table 1.3.6.

Table 1.3.6: Annual Groundwater Recharge in 12 Stations' Catchments

Station Name	River Name	Area [km^2]	Rainfall (R) [mm/yr]	Runoff Coefficient (C)	Base Flow Index (BFI)	Groundwater Recharge (GWR) [mm/yr]	GWR/R
Abomsa	Arba	140	1,018	0.295	0.26	77	7.6%
Addis Alem	Berga	248	1,136	0.315	0.40	144	12.7%
Akaki	Akaki	884	1,198	0.276	0.28	91	7.6%
Awara Melka	Kesem	3,113	824	0.164	0.33	44	5.4%
Asgori	Teji	663	1,115	0.169	0.27	50	4.5%
Beke	Kesem	50	1,249	0.546	0.21	145	11.6%
Bello	Awash	2,569	1,098	0.101	0.74	82	7.4%
Ginchi	Awash	76	979	0.372	0.21	76	7.8%
Holeta	Holeta	119	1,220	0.322	0.39	154	12.6%
Melka Homble	Awash	7,780	1,066	0.162	0.52	90	8.5%

Station Name	River Name	Area [km^2]	Rainfall (R) [mm/yr]	Runoff Coefficient (C)	Base Flow Index (BFI)	Groundwater Recharge (GWR) [mm/yr]	GWR/R
Melka Kuntire	Awash	4,580	1,103	0.171	0.57	108	9.8%
Sire	Keleta	747	806	0.300	0.46	111	13.8%

Source: the Project Team, Data: Result of hydrology survey in this Project

1.3.4 Results of water balance analysis

The annual groundwater recharge in the divided 13 sub-basins (see Figure 1.3.2 and Table 1.3.1) is estimated in the same procedure as that in 12 stations' catchments. In this estimation, both BFI and runoff coefficient (C) are assumed to be the function of catchment area as shown below (see Figure 1.3.6 and Figure 1.3.7 also):

$$GWR = R \cdot C \cdot BFI$$

$$BFI = 0.121A^{0.170}$$

$$C = 1.090A^{-0.236}$$

where,
- *GWR*: Annual groundwater recharge (mm/year)
- *R*: Annual basin mean rainfall (mm/year)
- *C*: Runoff coefficient (-)
- *BFI*: Base flow index (-)
- *A*: Catchment area (km^2)

The annual rainfall over sub-basins is calculated on the basis of the point rainfall data by applying the Thiessen polygon method (see Figure 1.3.4 for the Thiessen polygons). The Thiessen ratio for each rainfall station is shown in Table 1.3.7 by sub-basins.

Table 1.3.7: Thiessen Ratio for Sub-basins

Sub-basin	Rainfall Station	Thiessen Ratio	Sub-basin	Rainfall Station	Thiessen Ratio
SB1-L	Asgori	0.557	SB4-L-U	Metehara (NMSA)	0.237
	Addis Ababa Obs	0.363		Nazeret	0.123
	Ambo Agriculture	0.080		Abomsa	0.641
SB1-R	Asgori	0.750	SB4-L-D	Metehara (NMSA)	1.000
	Ambo Agriculture	0.096	SB4-R	Metehara (NMSA)	0.298
	Woliso Giyon	0.149		Gelemso	0.101
	Hombole	0.005		Abomsa	0.601
SB2-L	Asgori	0.002	SB5-L	Metehara (NMSA)	0.411
	Addis Ababa Obs	0.306		Debre Berhan	0.384
	Debre Zeit(AF)	0.481		Addis Ababa Obs	0.064
	Hombole	0.094		Debre Zeit(AF)	0.057
	Nazeret	0.116		Nazeret	0.084
SB2-R	Asgori	0.047	SB5-R	Metehara (NMSA)	0.143
	Debre Zeit(AF)	0.004		Gelemso	0.663
	Hombole	0.751		Meiso Mission	0.195
	Nazeret	0.008	SB-BSK-W	Metehara (NMSA)	0.443
	Melkasa(IAR)	0.057		Nazeret	0.535
	Kulumsa	0.133		Abomsa	0.021
SB3-L	Nazeret	0.445		Melkasa(IAR)	0.001
	Abomsa	0.012	SB-BSK	Metehara (NMSA)	1.000
	Melkasa(IAR)	0.544			
SB3-R	Nazeret	0.007			
	Abomsa	0.097			
	Melkasa(IAR)	0.494			
	Kulumsa	0.402			

Source: the Project Team, Data: Result of hydrology survey in this Project

The annual basin mean rainfall over sub-basins is calculated by applying the Thiessen ratios given in the table. Then, annual basin mean rainfall is multiplied by the runoff coefficient and BFI, which are estimated using the equations stated above. The annual groundwater recharge is estimated as in Table 1.3.8.

Table 1.3.8: Result of Groundwater Recharge Estimation by Sub-basins

SL No.	Sub-basin	Area (A) [km^2]	Annual Rainfall (R) [mm/yr]	Runoff Coefficient (C) [-]	Base Flow Index (BFI) [-]	Annual Groundwater Recharge (GWR)		GWR/R [%]
						[mm/yr]	[10^6 m^3/yr]	
1	SB1-L	2,068	1,097	0.18	0.44	87.2	180.3	7.9%
2	SB1-R	2,508	1,075	0.17	0.46	84.4	211.6	7.8%
3	SB2-L	4,860	982	0.15	0.51	73.7	358.4	7.5%
4	SB2-R	1,859	867	0.18	0.43	69.4	129.0	8.0%
5	SB3-L	508	853	0.25	0.35	74.4	37.8	8.7%
6	SB3-R	2,743	832	0.17	0.46	64.9	178.1	7.8%
7	SB4-L-U	435	824	0.26	0.34	72.5	31.6	8.8%
8	SB4-L-D	312	548	0.28	0.32	49.3	15.4	9.0%
9	SB4-R	3,367	806	0.16	0.48	62.0	208.8	7.7%
10	SB5-L	5,710	779	0.14	0.53	57.9	330.8	7.4%
11	SB5-R	2,347	870	0.17	0.45	68.6	161.0	7.9%
12	SB-BSK-W	2,041	740	0.18	0.44	58.9	120.2	8.0%
13	SB-BSK	532	548	0.25	0.35	47.6	25.3	8.7%
All Basin		29,290	876	-	-	67.9	1,988.3	7.7%

Source: the Project Team, Data: Result of hydrology survey in this Project

The estimated groundwater recharge ranges between 47 mm/year and 87 mm/year and is equivalent to 7.4%–9.0% of the annual rainfall. It has been reported that the annual mean groundwater recharge in the Awash River Basin (112,700 km^2) is about 3,800 million m^3 (33.7 mm/year), and this is equivalent to 9.5% of the available water from rainfall in the basin, which is 39,845 million m^3 (354 mm/year)[4]. Therefore, the groundwater recharge estimated here is considered reasonable though the result may be conservative to some degree.

The water balance in each sub-basin is estimated as in Table 1.3.9 by assuming that all losses are incorporated in the form of evapotranspiration.

Table 1.3.9: Water Balance in Sub-basins

SL. No.	Sub-basin	Area (A) [km^2]	Incoming	Outgoing		
			Annual Rainfall (R) [mm/yr]	Direct Runoff [mm/yr]	Base Flow (Groundwater Recharge) [mm/yr]	Evapotranspiration [mm/yr]
1	SB1-L	2,068	1,097	110	87	900
2	SB1-R	2,508	1,075	100	84	891
3	SB2-L	4,860	982	71	74	837
4	SB2-R	1,859	867	90	69	707
5	SB3-L	508	853	139	74	639
6	SB3-R	2,743	832	75	65	692
7	SB4-L-U	435	824	141	73	610
8	SB4-L-D	312	548	105	49	394
9	SB4-R	3,367	806	67	62	677
10	SB5-L	5,710	779	52	58	669
11	SB5-R	2,347	870	83	69	719
12	SB-BSK-W	2,041	740	75	59	607
13	SB-BSK	532	548	88	48	412
All Basin		29,290	876	78	68	730

Source: the Project Team, Data: Result of hydrology survey in this Project

Reference

(1) The Study on Groundwater Resources Assessment in the Rift Valley Lakes Basin in the Federal Democratic Republic of Ethiopia, JICA, 2012

[4] http://www.iwmi.cgiar.org/assessment/files/pdf/publications/WorkingPapers/WaterofAwasBasin.pdf