2. The Study Site

Lake Abaya is part of the Lake Abaya-Lake Chamo basin (Bekele, 2001), located in the southern sector of Ethiopian Main Rift (WoldeGabriel, 2002). It is the second largest lake in Ethiopia and the largest of eight Ethiopian Rift Valley lakes (Figure 2.1). Lake Abaya is elongated in shape and oriented in a north-east–south-west direction, parallel to the main trend of the Main Ethiopian Rift. Recent bathymetry has been published by Bekele (2001), and the basin parameters are shown in Table 2.1. Lake Abaya is a quasi-endorheic lake-system fed by rivers originating from adjoining highlands in the west and east escarpments (Figure 2.2). It drains ephemerally to the south into the adjoining Lake Chamo by overflow of the separating, c. 2 km wide sill during high lake levels. The surface of its open water body (excluding the islands) totals *c.* 1070 km^2, with a shoreline length of approximately 1000 km.

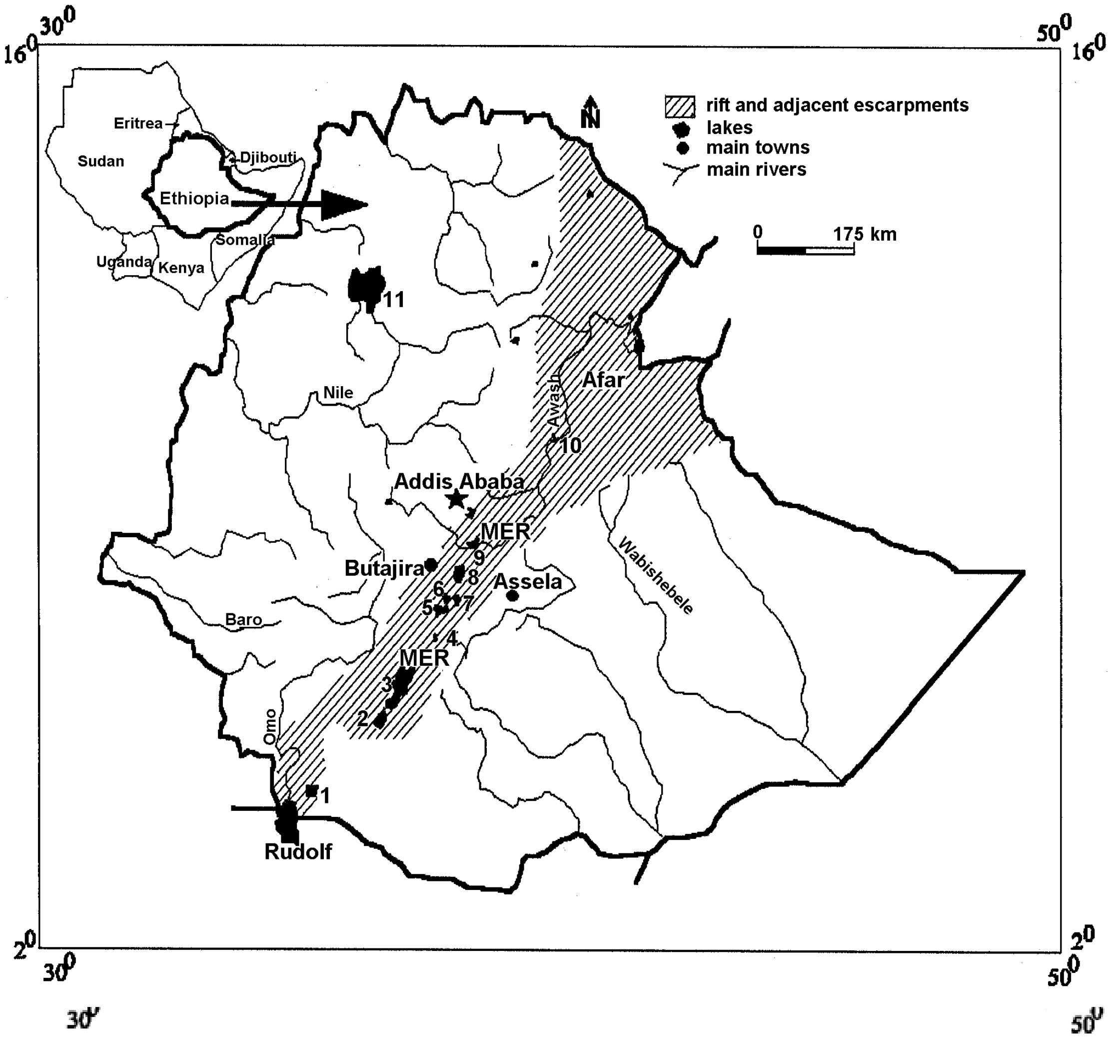

Figure 2.1. Ethiopia and the Ethiopian Rift Valley (hatched signature). In the Main Ethiopian Rift Valley natural lakes are endorheic. Lakes are indicated by numbers: 1:Chew Bahir; 2: Chamo; **3: Abaya**; 4: Awassa-Chelelka; 5: Shala; 6: Abiyata; 7: Langano; 8: Ziway; 9: Koka Dam; 10: Beseka (copied from Ayalew, 2001).

Table 2.1 Lake Abaya catchment and basin parameters: Source Bekele (2001)

Elevation, m	1169
Lake surface area (including islands), km^2	1139.8
Tributary area, km^2	16342.2
Volume, V, km^3	9.82
Mean depth, m	8.6
Maximum depth, m	24.5
Mean width, km	14.1
Maximum width, km	27.1
Shoreline, km	1001*

* Modified from Ethiopian Mapping Agency map of 1979 based on Satellite Image of NASA (2002).

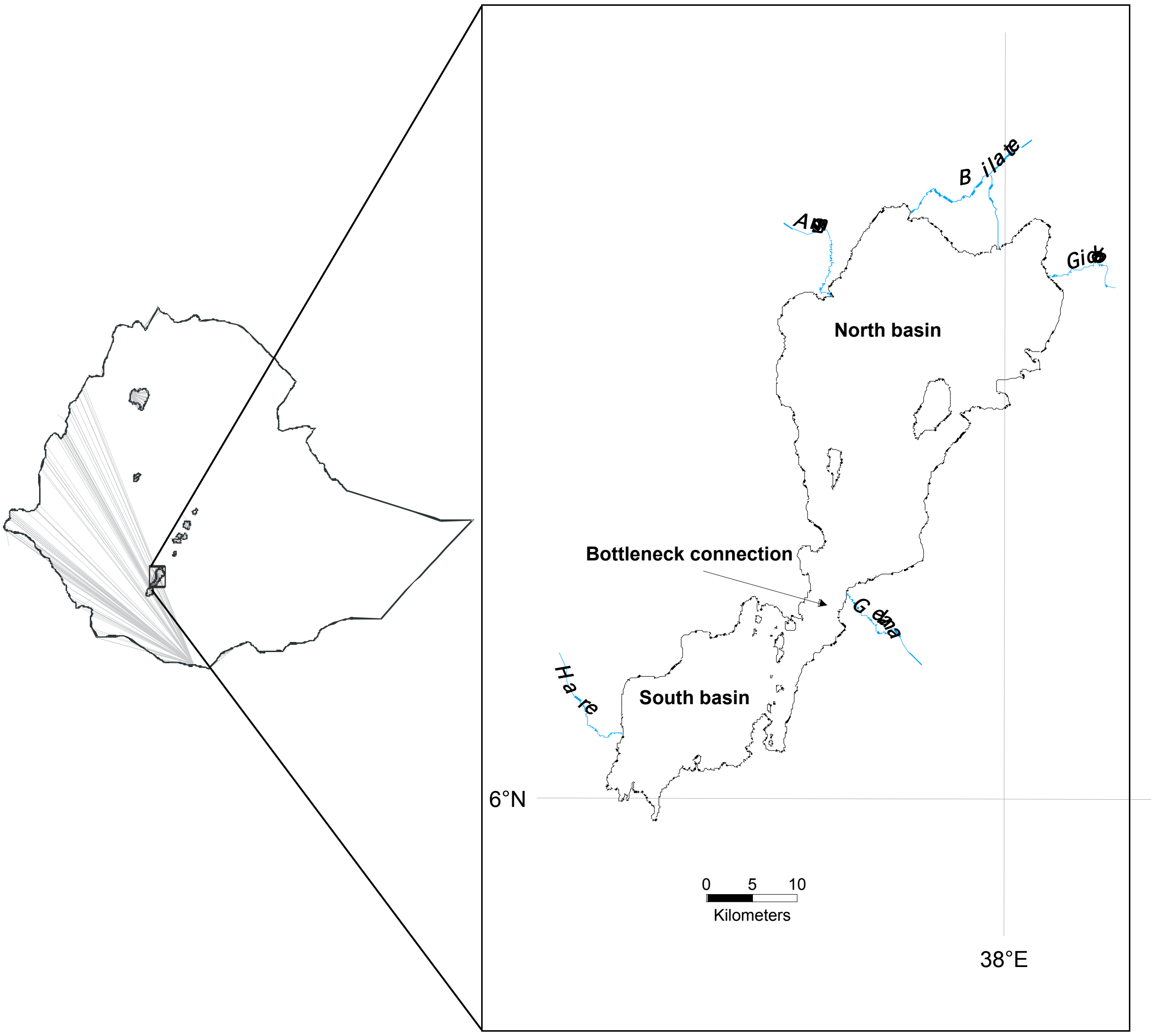

Figure 2.2. Main basins of Lake Abaya and location of main tributaries.

From morphological perspective, Lake Abaya drainage basin includes two main provinces–uplands consisting of faulted ridges and dissected piedmonts in the west and east escarpments and lowlands in the rift floor (Makin *et al.,* 1975). Climate, hydrology and geology are distinctly different in these two main physiographic provinces. The land surface of the drainage basin generally slopes gently from the edge of the valley floor toward the Lake Abaya in the valley floor from both the eastern and western sides. The distance between the edge of the valley floor and the shoreline is variable, the maximum in the western and eastern sides being about 7 km and 20 km, respectively. The western slopes of the basin, which cover the major part of the drainage basin, are steeper and more rugged than the eastern slopes. The elevation differences of the tips of the rolling hills at both shoulders also vary considerably, reaching up to 2800 m a.s.l. within horizontal distance of 20 km from the shoreline in the west and, up to 2325 m a.s.l. within 15 km from the eastern shoreline.

2.1. Climate

The drainage basin of Lake Abaya has a diverse climate, mainly owing to the range in altitude (from 1169 m a.s.l. at lake water surface to 3568 m a.s.l. at Wisha Ridge), and latitude corresponding to the position of the Inter-Tropical Convergence Zone (ITCZ) (Grove *et al.,* 1975; Gemechu, 1977; Bekele, 2001). The broad characteristics of the climate are alternating wet and dry seasons following the annual movement of the ITCZ, which separates the air streams of the northeast and southeast mansoons (Nicholson, 1996; Muchane, 1996). They are determined largely by the convergence of dry north-easterly winds with moist winds of south-easterly or south-westerly origin (Makin *et al.,* 1975; Baxter, 2002). Passage of ITCZ is associated with intensified convective activity within the air column, which usually leads to abundant rainfall (Rozanski *et al*., 1996). Stations located at the region of maximum southward or northward displacement of ITCZ reveal one rainy period, whereas those stations in the equatorial region experience two rainy periods associated with northward and southward passage of the ITCZ (Rozanski *et al*., 1996; Muchane 1996). The dry season occurs when the rainfall belts shift south and the area is influenced by dry northeastern trades originating in Arabia and Northeast Africa (Muchane 1996).

The large-scale tropical controls of climate variability in eastern Africa, which include several major convergence zones, are superimposed upon regional factors associated with influences of lakes and topography, resulting in markedly complex climatic patterns that change rapidly over short distances (Nicholson, 1996). As a result, the climatic patterns are markedly complex and change rapidly over quite short distances and altitudes (Grove *et al*., 1975; Nicholson, 1996)

Rainfall is the most significant climatic factor in tropical Africa, which affects the water resources including replenishing lakes and ground water storages (Balek, 1977). The nature of spatial and temporal variability of precipitation in Lake Abaya drainage basin is examined in detail using the 27 year monthly precipitation database corresponding to 22 stations first described by Bekele (2001). The spatial distribution of the rain gauge stations shown in Figure 2.3 is sparse and heterogeneous. The distance between the rain gauges varies between 11 and 86.4 km, with an average value of 81.5 km. Maximum over all distance between two stations is more than 240 km. The stations are situated in a complex topography with elevations ranging from 1199 to 2840 m *a.s.l.*

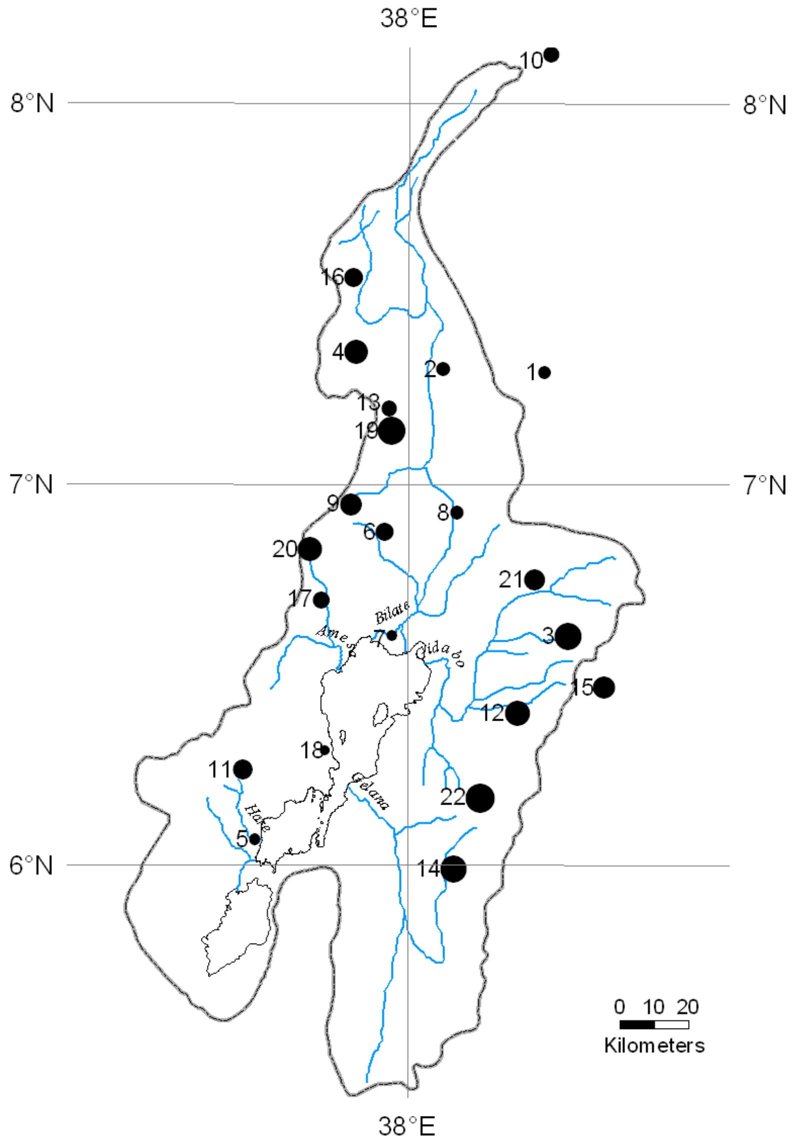

Figure 2.3. Location of Lake Abaya and positions of rain gauge stations: 1, Aje; 2, Alaba Kulito; 3, Aleta Wondo; 4, Angecha; 5, Arba Minch; 6, Bedessa; 7, Bilate Farm; 8, Bilate Tena; 9, Boditi; 10, Butajira; 11, Chencha; 12, Dila; 13, Durame; 14, Fiseha Genet; 15, Hagere Selem; 16, Hosaina; 17, Humbo Tebela; 18, Mirab Abaya; 19, Shone; 20, Sodo; 21, Yirga Alem; 22, Yirga Chefe. Circles correspond to the mean annual precipitation.

Figure 2.3 shows the average annual rainfall measured in the period 1966–1970, according to the data from Bekele (2001). Topographic effects cause substantial variability in mean annual precipitations in the drainage basin. Average annual values for the study period vary from below 800 mm in the vicinity of Lake Abaya to more than 1200 mm along the eastern and western highs, and reach more than 1600 mm along the eastern highs. Mean annual values reveal that precipitation is considerably enhanced by elevation and the rift valley floor posses the lowest annual average precipitation. Highlands flanking the Rift valley intercept most of the monsoonal rainfall in the region, resulting in a strong moisture deficit in the rift valley floor in general and near the lakes in particular (Legesse, *et al.*, 2003; Legesse, *et al.*, 2004).

Recent rainfall variations with elevation in Lake Abaya-Chamo drainage basin have been documented by numerous authors. Relationship of rainfall with altitude is compared using 27 years records 1970–1996 (Bekele, 2001; Thiemann and Förch, 2004), and 7 years records 1988–1994 (Krause *et al.*, 2004) at different stations in the drainage basin. Bekele (2001) suggests moderate correlation, whereas Krause *et al.* (2004) provide strong relationship until 2000 m a.s.l. between elevation and rainfall. On the other hand, Thieman and Förch (2004) found that precipitation patterns during the dry seasons of the wet years do not seem to be dependent on altitude at all. Thiemann (2006) found that the average monthly precipitation totals for a period 1970–1996 can be described by an exponential equation for 9 months; for January the equation is linear, while no correlation between elevation and altitude could be detected for October and November.

The pattern of increasing rainfall associated with increasing altitude is modified in the high altitude area by the influence of the high mountains which may cause either rain shadows or areas of heavy orographic rainfall (Makin *et al.*, 1975). In the tropics rainfall variation with elevation is influenced by factors such as water vapour available for condensation and rate of ascent of air (Nieuwolt, 1977; Jackson, 1977; Linacre and Geerts, 1997; Barry and Chorley, 2003). While an increase in rainfall with height is commonly experienced this does not necessarily continue to the summit of the highlands (Jackson, 1977). Rainfall tends to decrease at places above a kilometre or two up a mountain, after the air has lost water lower down and temperatures of the ascending air have fallen to the extent that little water can be hold as vapour (Linacre and Geerts, 1997). The presence of trade-wind inversion may limit ascent above a certain altitude with resultant decrease in rainfall above it (Nieuwolt, 1977; Jackson, 1977; Barry and Chorley, 2003). A further explanation for the occurrence of maximum precipitation below the extensive highlands in the tropics, where horizontal advection of moisture is often limited, is based on the high instability of many tropical air masses (Nieuwolt, 1977; Barry and Chorley, 2003). Where mountains obstruct the flow of moist tropical air masses, the upwind turbulence may be sufficient to trigger convection, producing a rainfall maximum at low elevations (Barry and Chorley, 2003).

All rain gauge stations considered in the drainage basin show considerable degrees of precipitation seasonality. Traditionally, four seasons are considered in regions where distribution is bimodal: dry period from December-to-February (known as *Bega*), small rain season from March-to-May (known as *Belg*), main rain season from June-to-August (known as *Kiremt*) and transitional period from September-to-November (known as *Tsedey*). The general trend in seasonal precipitation across the drainage basin is shown in Figure 2.4 using arithmetic average monthly rainfall for the nine constituent stations with three stations from each of eastern and western highs and rift valley floor. The means of four seasons for selected stations is also shown in Figure 2.4. Both monthly and seasonal averages variability of the graphs for constituent stations in Figure 2.4 reveals noticeable areal homogeneity.

A bimodal seasonal distribution of rainfall occurs throughout the stations considered, with peaks usually in April–May and July–September. Months of primary peak in the western upland and secondary peak in the valley floor appear to be variable. The annual cycle of rainfall depicted in Figure 2.4 reveals that precipitation is more seasonal in the eastern highlands, with months of maximum main and secondary rains at all stations consistently being in May and October, respectively. The rift valley floor has, on the average, the main rain in *Belg* centring in May or in *Kiremt* centring in July. In the western highs there is higher monthly average rainfall in the rainy *kiremt* season from June to August, whereas the eastern highs have higher monthly averages during B*elg* season.

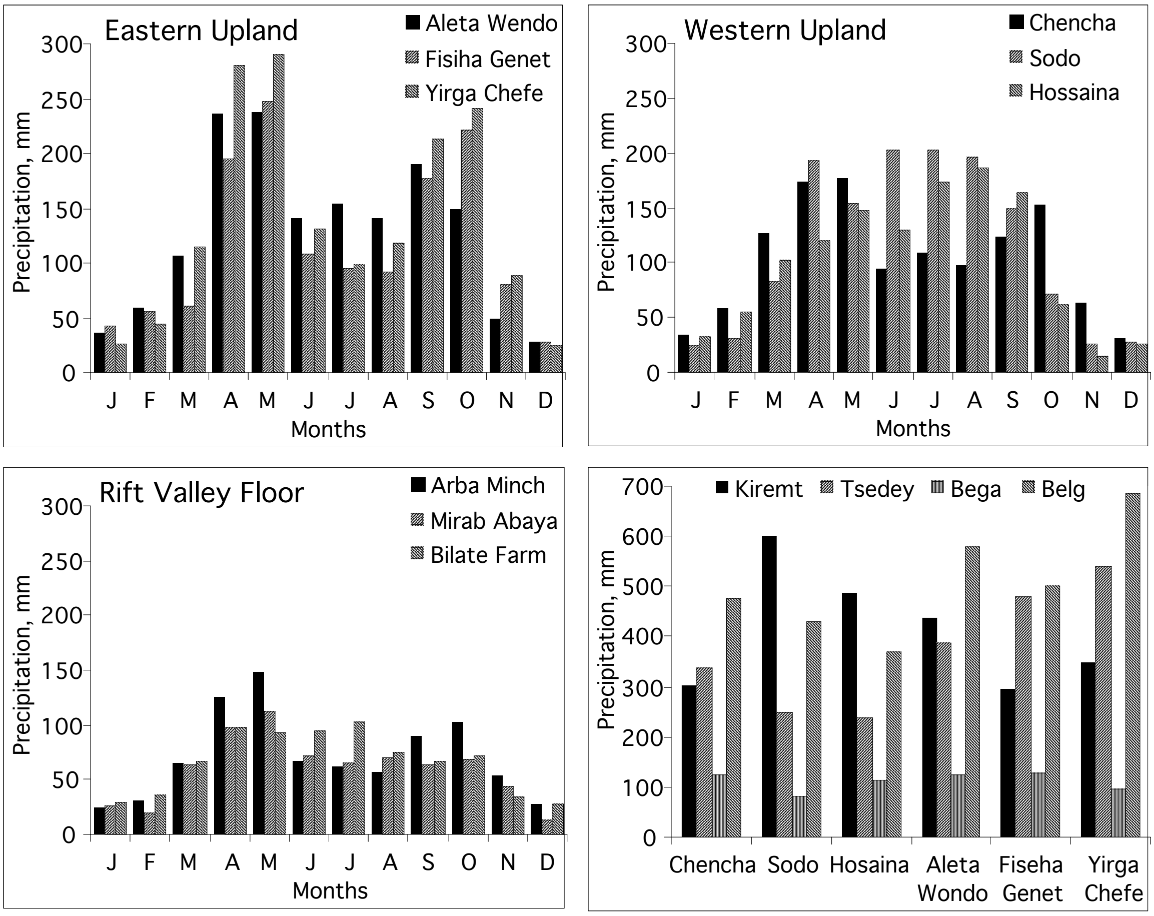

Figure 2.4. Mean precipitation by station location. Right bottom, Seasonal mean precipitation in the western and eastern uplands.

Seasonality of precipitation is further analysed quanititatively using Seasonality Index, *SI*, which provides a measure of the spread of the monthly rainfall withrespect to an idealy uniform monthly distribution in all 12 months (Celleri *et al.* 2007; Sumner *et al.* 2001). The *SI* derived by Walsh and Lawler (1980) is given by:

$$SI_i = \frac{\mathbf{1}}{R_i}\sum_{j=\mathbf{1}}^{j=\mathbf{12}}\left|M_{ij} - \frac{R_i}{\mathbf{12}}\right| \quad (1)$$

Where R_i is the total annual precipitation for the year i under study and M_{ij} is the monthly precipitation for month j. The above expression indicates that SI would be zero if the annual rainfall is distributed equally over all 12 months. Near zero values indicate that there is little or no seasonal variation of precipitation, with higher SI values representing a greater departure from uniform distribution through the year (see Table 2.2). However, Sumner *et al.* (2001) suggest that since such single figure corresponding to each station under investigation does not by itself provide a month-to-month detailed look at seasonal variation, it should be complemented by a detailed analysis of monthly precipitation across an area.

Table 2.2 Seasonal precipitation regimes as classified by Seasonality Index (after Walsh and Lawler, 1981)

SI	Precipitation regime
<0.19	Precipitation spread throughout the year
0.20–0.39	Precipitation spread throughout the year, but with a definite wet season
0.40–0.59	Rather seasonal with a short dry season
0.60–0.79	Seasonal
0.80–0.99	Markedly seasonal with a long dry season
1.00–1.19	Most precipitation in less that 3 months
>1.20	Extreme seasonality, with almost all precipitation in 1 to 2 months

The long-term mean index for each station can be calculated in two ways (Sumner *et al*, 2001; Celleri *et al.*, 2007). First, SI_i was computed for all 22 rain gauge sites within Lake Abaya drainage basin for each of 27 years of the data base. The long-term mean, SI_{mean}, for each site was derived by averaging the SI_i values computed for each year of the record over the study period, 27 years in the current study:

$$SI_{mean} = \frac{\mathbf{1}}{27}\sum_{i=\mathbf{1}}^{i=27} SI_i \quad (2)$$

The second alternative index, denoted by SI_a, was computed for each station using mean monthly and annual rainfall data in Equation (1) directly, but the resulting index will possess a lower magniture as a result of smothening by averaging the noise in the year to year distribution of monthly precipitation values (Sumner *et al.*, 2001).

The distribution of wetter periods throughout the year are indicated using the Replicability Index, RI, defined by Walsh and Lawler (1981) as:

$$RI = \frac{SI_a}{SI_{mean}} \tag{3}$$

Higher values of Replicability Index indicate that the wettest month of the year generally occurs in only the same few months, resulting a stable long-term intra-annual rainfall distribution. Conversely, a highly variable timing of wet and dry seasons will result in a smaller *RI* index.

The values of SI_{mean} for the period 1970–1996 at rain gauge stations in Lake Abaya drainage basin (Table 2.3) revealed reduced seasonality of eastern uplands, with higher values in the range 0.52–0.67, when compared to the the rift valley floor and western highs, where indices varying between 0.58 and 0.73. In the rift valley floor, value of SI_{mean} fall below 0.6 only at Bilate Farm, with the precipitation seasonality being reduced in the central areas. Higher values in the western margines of the rift valley floor attributed to the fact that the precipitation is relatively concentrated in two periods separated with marked dry season.

Table 2.3 SI_i mean values and years with extreme SIi for each rain gauge station.

Location	Station	SI_a	SI_{mean}	$SI_{minimum}$	Year	$SI_{maximum}$	Year	*RI*
Western Highland	Angacha	0.46	0.61	0.38	1992	0.85	1973	0.76
	Bedessa	0.45	0.60	0.29	1992	0.92	1988	0.76
	Boditi	0.48	0.58	0.29	1989	0.83	1984	0.83
	Chencha	0.39	0.60	0.29	1989	0.80	1970	0.65
	Durame	0.44	0.62	0.41	1976	0.90	1973	0.71
	Hossaina	0.52	0.65	0.41	1989	0.87	1973	0.80
	Humbo Tebela	0.51	0.64	0.45	1989	0.83	1981	0.80
	Shone	0.41	0.58	0.30	1977	0.86	1974	0.70
	Sodo	0.61	0.69	0.32	1989	1.07	1973	0.88
Rift valley floor	Aje	0.51	0.70	0.39	1992	1.04	1984	0.73
	Alaba Kulito	0.42	0.61	0.32	1977	0.89	1981	0.69
	Arba Minch	0.43	0.64	0.34	1978	0.86	1985	0.66
	Bilate Farm	0.35	0.59	0.31	1982	0.85	1981	0.59
	Bilate Tena	0.41	0.60	0.30	1982	0.84	1974	0.69
	Butajira	0.53	0.73	0.49	1977	1.07	1984	0.72
	Mirab Abaya	0.38	0.69	0.45	1980	1.02	1981	0.54
Eastern highland	Aleta Wendo	0.47	0.57	0.39	1989	0.71	1983	0.81
	Dila	0.41	0.55	0.31	1978	0.72	1979	0.74
	Fisiha Genet	0.53	0.62	0.43	1989	0.75	1982	0.85
	Hagere Selam	0.40	0.52	0.35	1972	0.71	1975	0.76
	Yirga Alem	0.44	0.58	0.31	1982	0.77	1989	0.76
	Yirga Chefe	0.56	0.67	0.44	1989	0.90	1980	0.84

As Sumner *et al.* (2001) pointed out, mean values may mask considerable annual variability in the SI_i. Indices exceeded once or twice 1.0 in individual years within the study period, and have occurred along the western part of the rift valley floor and sholder. In the eastern uplands, the lowest SI_i values recorded for individual years are generally around 0.3 or 0.4, while the highest values exceeded rarely 0.8 only at Yirga Chefe. This indicates that most of the eastern uplands do not experience a marked seasonality even in extreme years, suggesting eastern part of the drainage basin is more reliable year-round water provider. The highest value obtained for individual years is 1.07 (Sodo and Butajira stations) and the lowest is 0.29 in the western upland towards far south (Chencha Station) and around the central area (Bedessa and Boditi stations).

The occurrence of the minimum and maximum values of the indices in Table 2.3 simultaneously at nearby stations indicates the existance of rainfall subregions. The lowest indices occurred over many parts of the western and eastern uplands during 1989, when they experienced wet year with only one or two dry months (<50 mm monthly rainfall) and little marked variation in precipitation in remaining months. Increased seasonality occurred in some areas in the western uplands during 1973, when >50% of the annual precipitation occurred within 2 or 3 months with 2 or 3 consecutive months having <50 mm monthly rainfall amount. Overall, the importance of local orography over the large-scale anomalies is implied by the fact that minimum and maximum values of the indices do not occur simultaneously all over the drainage basin as shown in Table 2.3.

Replicability Index (*RI*) values varied between 0.54 and 0.88, with overall higher values found in the western and eastern uplands and the lower values in the rift valley floor. The smallest value corresponding to the station at Mirab Abaya reflected that every month (with the except of January and February) has been at least once the wettest month of the year. Therefore relatively smaller *RI* values in the rift valley floor represents the characteristics of having a higher flactuation of the timing of the wettest period of the year compared to the surrounding highlands. The highest value corresponding to Sodo station indicates that months with the highest rainfall in individual years are more restiricted consistently to a few months (between June and August in 18 out of 27 years), resulting fairly stable annual precipitation pattern.

Overall, the above results of seasonality analysis demontrated the complexity of rainfall pattern in the drainage basin. The occurrence of different rainfall patterns over relatively small distances and altitudes in the drainage basin implies that the climate is controlled to a large extent by the regional factors (Nicholson, 1996). As noted by Nieuwolt (1977) for east Africa climate variability, Lake Abaya and Chamo in the valley floor produce huge amounts of water vapour and also create local disturbances conducive to rainfall. Other local factors leading to complex pattern of rainfall include numerous highlands and differences in exposures.

The dry season usually extends between November and February when ITCZ is in the south of Ethiopia, and the northeasterly trade winds traversing Arabia dominate the region (Muchane, 1996; Vallet-Coulomb *et al.*, 2001; Legesse, *et al.*, 2004). Two rainy periods (known as *belg* and *kiremt* rains) are associated with northward and southward passage of the ITCZ, respectively (Rozanski *et al.*, 1996; Muchane, 1996). In general, the main rains in most of the drainage area occur during the period July to October when the ITCZ lies around the north of the country so that the resulting convergence of the wet monsoonal current from the Indian and Atlantic Oceans brings much rain to the region (Malkin, 1975; Vallet-Coulomb *et al.*, 2001; Legesse, *et al.*, 2004). At the same time, low pressure over India and the Arabian Sea dominates airflow and generates strong, persistent southwesterlies to the southern part of Ethiopia. Convective instability, due to the intense heating of the high plateau land, is also a cause of a high percentage of the rainfall (Legesse, *et al.*, 2004). Incursions of the humid, unstable westerly Congo air stream during this time (Niuvoult, 1971, Nicholson, 1996) bring high rainfall over the western part of the drainage basin. Lesser rainfall in the western highlands and main rainfall in the eastern highlands in the *belg* season coincide with a decrease of the Arabian high as it moves towards the Indian Ocean causing warm, moist air with a southerly component to flow over the southeastern half of the country (Vallet-Coulomb *et al.*, 2001; Legesse, *et al.*, 2004).

Rainfall intensity is the most important parameter for the investigation and prediction of flood generation and soil erosion (Merz *et al.*, 2006). However, rainfall intensity information at high temporal resolution is scarce in Lake Abaya drainage basin due to absence of recording rain gauges. The high-resolution (0.1 mm/impulse) recording rain gauge at Wajifo Weather Station established for this study measured maximum 1 minute rainfall amount of 9.3 mm (equivalent to 588 mm hr^{-1}) on 3 September 2004. The maximum 5 and 10 minutes intensities observed at this station were 176.4 and 94.2 mm hr^{-1}, respectively, during the period March 2004 – February 2005. The highest 1 hr measurement observed at this station was 23.7 mm 0n 7 April 2004.

Annual rainfall recorded at Wajifo Weather Station during March 2004–February 2005 was about 815 mm (Figure 2.5). One main rainy month (April with >200 mm) enclosed by pronounced dry months (March and May each with <25 mm). June to October and November to December were fairly rainy months, each with >55 mm. Close examination of continuous records reveals that the most intense 3 hour storm with a total of 60 mm form 30% of the monthly total precipitation in April 2004. About 40% of the annual rainfall emerged from June through September. These evidences illustrate that in the tropics a high proportion of annual rainfall is concentrated into a relatively small number of days (Makin *et al.,* 1975; Balek, 1977).

Examination of rainfall events on a daily base further shows that 83 rainy days (i.e. days with rainfall amount of 1mm or more) measured annually (from March 2004 – February 2005). These rainy days mostly measured between 1 and 10 mm (about 65 percent of all the rainy days). In terms or rainfall amounts, these days contribute about 23 percent of the total annual rainfall. The frequency distribution of daily rainfall is highly skewed to the left showing that low-magnitude rainfall is much more frequent that high-magnitude rainfall. Days of more than 25 mm account for only 6 percent of the rainy days with a maximum of 66.2 mm measured on 13 April 2004.

Diurnal variation of rainfall indicates that most of the rainfall occurs from 1800 to 0600 hr local standard time (LST). About 72 percent of the annual rainfall from March 2003 to February 2004 occurred during the night, in particular early in the morning between midnight and 0600 LST. This suggests that the nocturnal-early morning rain type did appear to predominate, which confirms the costal type diurnal rainfall regime in the tropics (Nieuwolt, 1977; Reihl, 1979).

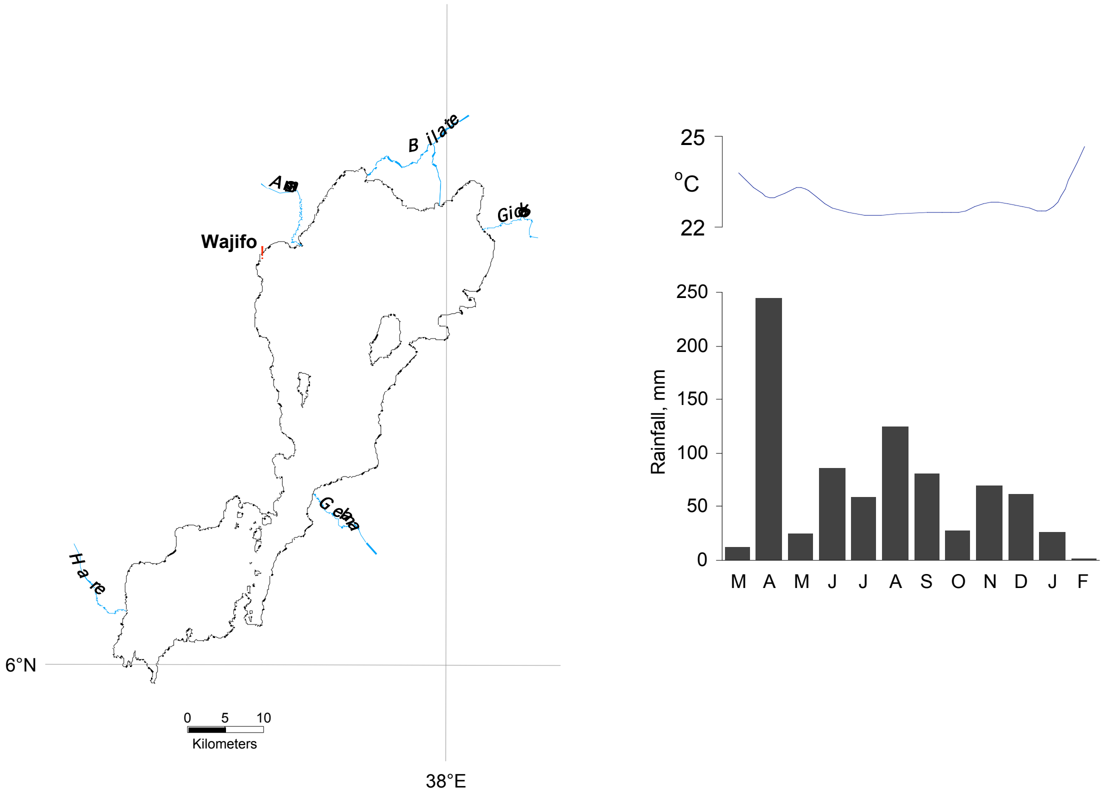

Figure 2.5. Left: Location map; Right: monthly rainfall and average air temperature at Wajifo.

In the tropics, the character of rainfall in a particular month (e.g. intensity, duration, frequency) and the elements of atmosphere–soil–plant system determining the effectiveness of the rainfall in relation to evaporative demand make it impossible to strictly define a 'wet' month (Jackson, 1977). Next to rainfall, evaporation and evapotransportation, both under the influence of sunshine, are the most significant phenomena in the hydrological cycle (Balek, 1977; Jackson, 1977). In the lowlands of the Lake Abaya drainage basin temperature and water losses are high and rainfall amounts are low (Gemechu, 1977). Because evapotranspiration exceeds the rainfall in the Ethiopian Rift Valley area, the closed drainage basins may suffer seasonal or annual water deficits (Todorancea and Taylor, 2002). The humid and rugged conditions in the highlands, from which the streams flow, encourage rapid runoff, low retention in soil layers and soil erosion (Gemechu, 1977).

2.2. Hydrology

Lake Abaya receives water from precipitation on the lake as well as tributaries around it. The arrangement of rift segments affects the location, pattern and flow direction of major drainage system (Wescott, *et al*., 1996). The major rivers rise from the plateau on either side of the rift and follow in a radial manner into the lake. The north basin has four main inflows, which have their sources in the Ethiopian highlands. The south basin has only the Hare River as larger inflow, with its headwater area in the Western Ethiopian Highlands. All rivers are perennial in their upper reaches, and have the character of allochtonous rivers at the graben floor. Yet most of the runoff is captured during dry season for irrigation in the lowland areas around the lake (Bekele, 2001; WoldeGabriel, 2002). Lake Abaya lacks a direct surface outlet and drains down to Lake Chamo by overflowing the sill in its south end (Schütt *et al.,* 2005).

The catchment area of the gauged main tributaries varies between 199 and 5224 km^2 (Schütt *et al.,* 2005; Bekele, 2001). Bilate River, which has the largest catchment area among the main rivers, rises 100 km south of Addis Ababa and flows south between the headwaters of the Omo River to the west and the central Main Ethiopian Rift lakes to the east (Grove, 1975; Bekele, 2001; Schütt *et al.,* 2005). Runoff of the major rivers is unregulated. They receive water from several tributaries on their way to Lake Abaya. Next to these major tributaries numerous first and second order streams, mainly torrential, enter into the lake. Most of these river courses can be characterized upstream as straight and with high velocity-steep gradient runs, and downstream as flood plains with braided systems. The bulk of the infill material accumulated in large fans at the rift floor is of high pore volume and, thus, serves as an important near-surface groundwater storage (Makin *et al.,* 1975; Grove, 1986).

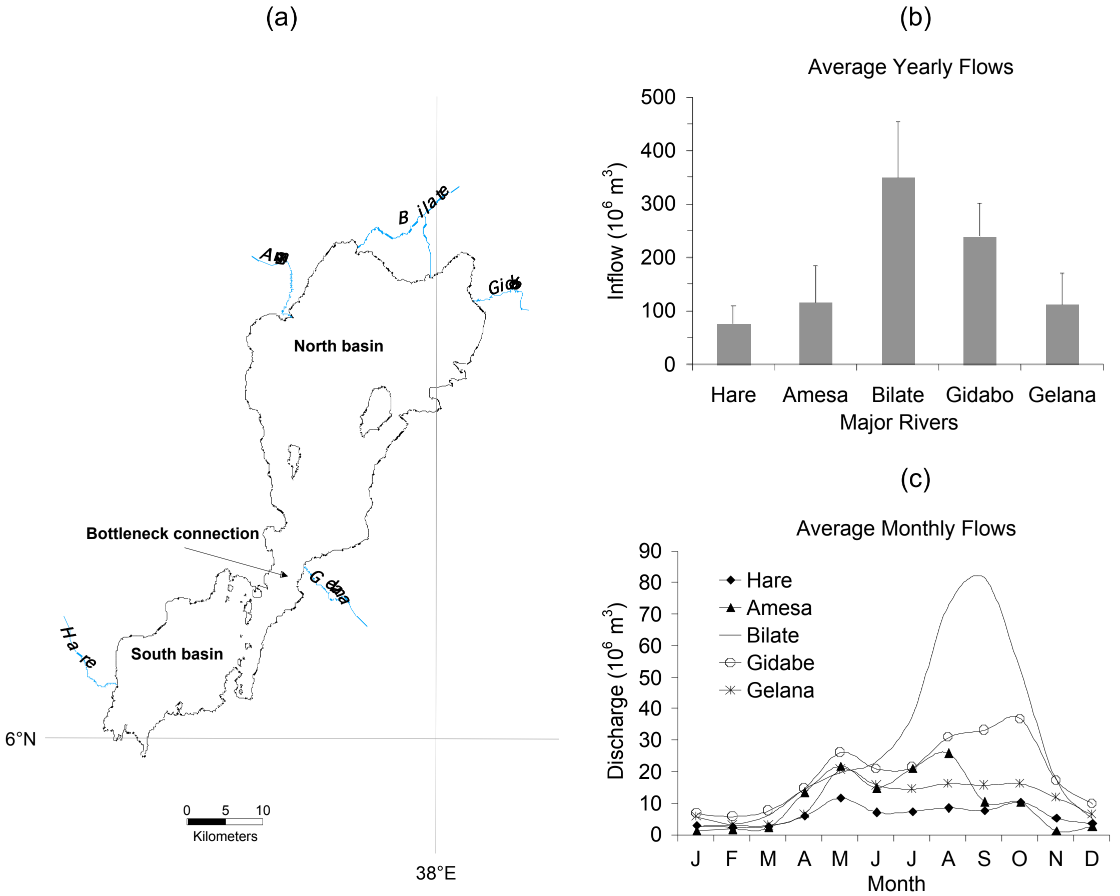

Figure 2.6. Location map of major tributaries around Lake Abaya (a), and their yearly average (+s.d.) (b) and monthly average (c) inflows. Data Source: Ministry of Water Resources.

Freshwater discharge into the south basin contributes only small amount compared to the total input in the north basin. Volumetric records at gauged main tributaries (1970–2003) show that Bilate River, mouthing in the north end of the lake basin, provided the largest (38%) of the mean annual total inflow, while the Hare River, the largest tributary of the south basin, provided only 9% of the mean annual total inflow (Figure 2.6b). An overwhelming majority of its mean annual water supply is provided by surface runoff from the major tributaries Amesa, Bilate, Gidabo, and Gelana in the north basin (Figure 2.6a). Moreover, except during flooding Hare River flow is basically intercepted for irrigation and inflow to the lake is virtually zero. In general, it is assumed that there is flow from the north basin to the south basin through the bottle neck, regulated and triggered by the inflow of the northern basin tributaries to satisfy continuity requirement.

Averages of monthly stream flow volumes of 34 year records are generally highest in the rainy months and decline during months with small or little rainfall in the drainage basin (compare with Figure 2.4). There is a clear variation in the seasonality of major rivers flow, which is demonstrated in Figure 2.6(c) using mean monthly flows for the period 1970–2003. While Figure 2.6(c) highlights months which have experienced large events, it should be remembered that the periods of record from the main rivers do not strictly overlap. Minimum stream flows occur from January to March, and begin increasing slowly in March in response to first rainy season (*belg*), with minor peak in May and annual peak between August and October resulting from direct runoff during the main rainy season for rivers draining from the north. On the contrary, rivers draining from southern drainage basin have main pick in May due to the greater intensity of the *belg* rain season and secondary peak in October as a result of general lack of or small rain between June and August. Discharge in the south is relatively stable from June to October, and overall declines quickly from October onwards.

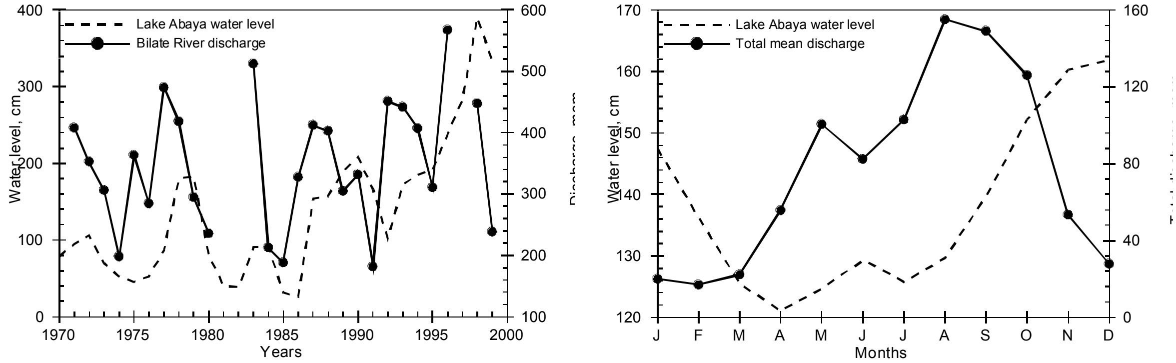

Figure 2.7 Interannual evolution and monthly distribution of lake water level at Arba Minch Station and discharge of Bilate River at Alaba Kuluto Station. Mean monthly distribution of discharge correspond to the sum of major tributaries.

The lake levels over time (1970–1999) are shown in Figure 2.7 and can be compared with the largest tributary Bilate River flow recorded at Alaba Kulito gauge station. However, according to Schuett and Thiemann (2004), who studied modern water level and sediment accumulation changes of Lake Abaya, a direct interrelation between inflow from tributaries and lake-level changes can not be stated mainly due to interception of flow downstream for increased irrigation demand and other purposes over recent years. Schuett and Thiemann (2004) further suggest that continuous increase of lake-level in the recent past could be attributed to increased sediment input due to land use changes and neo-tectonism due to location of the lake in the most active tectonic zone. Some changes in lake levels in the Ethiopian rift are possibly due to the formation and/or reactivation of rift faults (Yalew, 2004).

During 30 years period (1970–1999), the available data show that the lake have undergone water level variations of more than 4 m in amplitude. The large proportion of rainfall and evaporation in the balances of the African lakes makes their levels particularly sensitive to climate change (Spigel and Coulter, 1996). Plots of mean monthly lake level records near Arba Minch and total inflow of major tributaries (Figure 2.7) demonstrated their seasonality. The sum of mean monthly inflow of major tributaries showed seasonal input with annual maximum in August and secondary peak in May, whereas the monthly distribution of mean lake level is found to have its respective maxima in December and June. Seasonal influences on the East African lakes are dominated by the annual cycle of monsoon winds and the accompanying changes in air temperature and humidity (Spigel and Coulter, 1996).

The beginnings of increase in lake level at Arba Minch station situated near the south end of the lake during primary and secondary rainy seasons lag by one and two months, respectively, the start of total inflow to rise. This onset of lake water lever rise at the south end earlier after beginning of increase in total mean inflow suggests that stronger lake water circulation prevailing during main rainy season distributes faster the freshwater and sediment input by major tributaries principally from the north basin. Put another way, the average strength of circulation during the main rainy season (*kiremt*) is about twice the average speed of lake water currents prevailing in the *belg* season.

2.3. Lake water quality

The water of Lake Abaya is characterized as alkaline – saline with dominant ions of sodium, bicarbonate and chloride, and smaller concentrations of potassium, calcium and magnesium among cations and suphate and fluoride among anions (Kebede *et al.*, 1994; Baxter, 2002; Teklemariam, 2005). It is found to be the most concentrated water of the lakes in the country having outlets, perhaps because its discharge into Lake Chamo is only intermittent (Baxter, 2002). Concentration of fluoride is high enough to induce fluorosis with mottling of the teeth in the inhabitants in Gidicho Island in the northern basin and around the lake.

The transparency of the lake water is very low as the Secchi disc readings show (Kebede *et al.,* 1994). Light attenuation in these lakes appears to be mostly due to suspended inorganic material (Baxter, 2002). The lake water is of a reddish colour due to very stable suspension of colloidal ferric oxide particles in the water column, which are introduced by most of the tributaries and distributed all over the whole water body (Schröder, 1984). This is documented by the fact that the concentration of Iron is found to be quite high (10 mg/l) (Baxter, 2002). The electrolyte concentration of the water seems to be critical in maintaining the stability of this suspension (Wood *et al.,* 1978).

Comparison of data on salinity of Lake Abaya over years showed marked increases between the 1930s and the early 1960s (Wood and Talling, 1988; Baxter, 2002), and it falls until 1980, after which there is a rapid increase in salinity and later evening out to a gradual increase.(Teklemariam, 2005). The former trend may suggest that the lake received saline flows and lies in an area of intense heat and consequently a high rate of evaporation. For example, Bilate River receives saline springs in its lower reaches and this contributes to the salinity of Lake Abaya (Makin *et al.*, 1975). Evaporation, which is considered as a major component of tropical African lakes water balance, played an important role in giving the unique hydrogeochemical signature of most of the lakes (Vallet-Coulomb *et al.*, 2001; Alemayehu *et al*., 2006).The later phenomenon may be correlated with the decrease in water level of Lake Abaya in the period 1980 – 1989 mainly caused by a meteorological drought phase leading to reduced peaks and volumes in precipitation (Teklemariam, 2005). Generally, water input-output relationships are the dominant feature of the status of the salinity series of the rift lakes (Wood and Talling, 1988). If accompanied by a maintained lake level or volume and negligible seepage-out, evaporation loss can balance inflow plus direct rainfall; thus, with time, the lake becomes more saline (Alemayehu *et al*., 2006).

Overall, the present day hydrochemistry of the rift lakes is the result of long-term hydrogeochemical evolution of the lacustrine system and the flux of coming and going out of the lakes through the Quartnary sediments (Teklemariam, 2005; Alemayehu *et al*., 2006). These lakes accumulated solutes from inflowing rivers, rainfall and groundwater sources. Subsequent evaporative concentration (especially in closed terminal lakes) has led to the precipitation of certain minerals and concentration of others. This profoundly affected the composition of the remaining water (Alemayehu *et al*., 2006). The source of the present day composition of the terminal lake waters is, therefore, particularity difficult to interpret on the basis of present day inflow and outflow conditions alone (Alemayehu *et al*., 2006).

2.4. Geology

Lake Abaya lies in the main graben of the Ethiopian Rift System, which consists of three major rift zones with distinct volcanic and tectonic characteristics that are at different stages of rifting: the broadly rifted zone of south western Ethiopia, the Main Ethiopian Rift (MER) of central Ethiopia, and the Afar Rift System (WoldeGabriel, 2002). Lake Abaya, which is situated in the southern segment of the Main Ethiopian Rift, is one of the numerous fresh and saline lakes in the central sector of the Ethiopian rift that form hydrogeologically a unique system within the rift due to the underground interconnection by NE–SW aligned regional faults (Alemayehu *et al.*, 2006).

Volcanism and tectonism have been major controls on the development of lakes and drainage pattern in the East African Rift System (Wescott *et al.*, 1996). Volcanism started in the southern and central sectors of the MER as early as in Eocene time with important basaltic eruptions, associated with an early stage of rifting characterized by uplift and faulting (WoldeGabriel, 1990; Ebinger *et al.*, 1993). From Late Oligocene to Early Miocene times, the first major phases of rifting within the MER resulted in a series of asymmetric half-grabens with alternating polarity (Le Turdu *et al.*, 1999). The volcanic products in many places were fissural basaltic lava flows, stacked one over the other, alternating with volcano-clastic deposites derived from tuff, ignimbrite, and volcanic ash (Alemayehu *et al.*, 2006).

Volcanic and tectonic activities that were responsible for the formation of volcanic plateau, uplift, eastern and western faulted margins of the MER, and development of rift basins began in the middle to late Miocene (Grove, 1986; WoldeGabriel *et al.,* 2000). Then, evolution from alternating half-grabens to full symmetrical graben occurred, and low angle volcanic piles were built up both at the margins of the rift floor and within it in the late Miocene and Pliocene (Grove, 1986; Le Turdu *et al.*, 1999). Smaller volcanoes within the rift, active until a few centuries ago, are now dormant or emit only steam (Grove *et al.,* 1975; Ayalew, 2004). A widespread thermal activity mainly characterized by hot sprints, fumaroles and altered grounds exists on the northwest shore of Lake Abaya (Grove *et al.,* 1975; Teklemariam and Beyene, 2005).

The opposing stepped fault zones forming the margins of the rift and spaced not more than 32 km apart (Jackson, 1971) cut across plateau lavas, tuffs, and ignimbrites of Tertiary age (Grove *et al.,* 1975). Both escarpments expose crystalline basement, sandstone of unknown age, and thick sections of Eocene to late Miocene mafic and silicic lavas and tephra (Ebinger *et al.,* 1993). Northwards along the rift floor and east of Sodo, the Bilate River and its tributaries expose Pleistocene fluvial and lacustrine sediments interbedded with basaltic lavas and ash flows and fallout (WoldeGabriel *et al.,* 2000). Sediments and tephra mostly cover the rift floor east of the Bilate River (WoldeGabriel, 2002). The Abaya (Ganjuli) basin is separated from the Chamo basin to the south by *Tosa Shucha* (Bridge of God), which is a chain of eruptive volcanic centres that crosses the rift valley (Ebinger *et al.,* 1993). The simplified geological map of the southern sector of Ethiopian Rift System that includes the main drainage basin of Lake Abaya is shown in Figure 2.8.

While the primary control on the origin of the lake is the faulting due to rift formation, difference in the length and offset of the normal faults will determine the original morphology of the troughs (Yuretich, 1982). On the rift floor, topographic barriers created by lava flows, uplift, and faulting created basins and lakes that act as a sediment trap (Grove, 1986; WoldeGabriel *et al.*, 2000). The bulk of the infill consists of material of volcanic origin, much of it airfall pumice and ash derived directly from eruptions, the rest transported by rivers (Grove, 1986). The most recent deposits around the lake and along the river valleys are alluvial fans and landslides (Makin et al., 1975; Halcrew and Patrners, 1992).

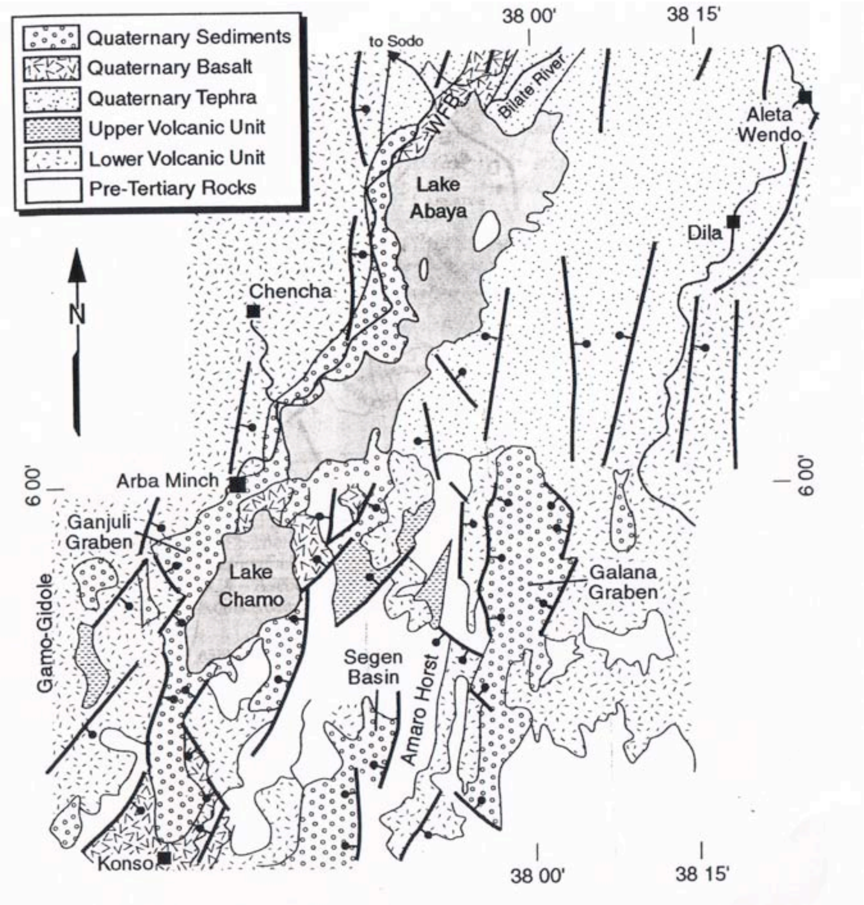

Figure 2.8. Geological map of southern sector of Ethiopian Rift Valley and adjacent plateau (WoldeGabriel, 2002).

2.5. Present day morphodynamics

Rivers draining through steep and severely gullied volcanic slopes to the rift floor bringing in heavy loads of fine detritus into the lake as it can be seen from the reddish-brown colour of the lake water (Grove *et al.,* 1975; Schröder, 1984; Schütt *et al.,* 2005). The abundance of easily-weathered volcanic material forming structurally weak topsoil that is highly prone to erosion contributes to the high rate of suspension load of the tributaries and sedimentation in the lake basin (Yuretich, 1982; Halcrow and Partners, 1992). Furthermore, dramatic population growth since the 1970s and clearing of forests and bush lands as a consequence, changes in land ownership and cultivation manners have induced increasing soil erosion processes, even aggravating erosion processes (Grove *et al.,* 1975; Schütt and Thiemann, 2004; Schütt *et al.,* 2005; Hurni *et al.,* 2005). Soils are potentially most erodible during rainy seasons before significant crop cover exists. Major part of rainfalls occur usually prior to significant crop cover – any leaf growth that has started was insufficient to shelter soils from raindrop impacts – thus, soils are highly susceptible to erosion. The scale of erosion is devastating in Bilate basin, north of Hasaina, north of Lake Abaya and between Dilla and Lake Abaya, with large expanses of land being lost each year (Halcrow and Partners, 1992). As a result, soil erosion and sediment loading to streams are concerns in Lake Abaya drainage basin.

Soil types in the drainage basin are closely related to parent material and degree of weathering; weathering has generally predominated over leaching and the presence of distinct layers within the soil profile is rare (Makin *et al.*, 1975; King and Birchall, 1975). The main parent materials are basalt, ignimbrite, lava, gneiss, volcanic ash and pumice, and riverine and lacustrine alluvium (Makin *et al.*, 1975). Much of the highland area frigging the Southern Rift Valley is characterized by deep reddish clay loams or clays developed from weathered basalt, where as the lowlands, including fans, deltas and floodplains around Lake Abaya, are characterized by soils formed on materials recently deposited by rivers (Makin *et al.*, 1975). Lacustrine deposits include bedded pumice, siltstone, sandstone and tuff (King and Birchall, 1975). On the plateau, above 2000 m, the basalt, tuff and ignimbrite with additional volcanic ash give rise to soils with high silt and clay contents (Makin, *et al.*, 1975).

Short sediment cores taken from the deltas of Bilate and Gidabo rivers in the north basin posses mainly soft and poorly consolidated clay size fraction deposits of 30–70 cm depth overlaid highly compacted sandy deposits (Schütt and Thiemann, 2004; Schütt *et al.,* 2005). Very fine laminations are typical for most samples collected from both deltas. This suggests that the sediments of Lake Abaya are laminated despite the fact that the shallow depth is subject to continuous wind-driven wave action. In other words, laminations are preserved because sedimentation rate is too fast to allow complete reworking by wind-driven wave action.

Quartz is the dominant mineral in the Bilate delta, but its concentration varies between minor to major at Gidabo delta. Organic carbon concentration is generally very low. Its distribution at Bilate delta shows uneven oscillation with depth yet generally decreases within 10 cm from the top. Samples from Gidabo delta have higher concentration of organic carbon, and showed similar variations with depth and sampling locations (i.e., at the centre and near margin of the delta). High concentration of clay minerals in the most recent delta deposits of the major rivers point out soil erosion process due to human impact in the drainage basins (Schütt *et al.,* 2005).

The paucity of organic carbon is a reflection of both the high rate of detrital sedimentation and the well mixed oxidizing environment of the overlying water mass (Yiretich, 1979). Since organic matter in natural waters is present in different forms, in suspended living and organic detritus, in true solution, and in colloidal solutions, variations in organic carbon content with depth is attributed to the efficiency of decomposition in relation to supply from different forms (Schütt *et al.,* 2005; Bordovskiy, 1965a, 1965b). Calcites, which are the only carbonate found in the lacustrine sediments from Lake Abaya, originated from organisms or evaporation respectively as the occurrence of limestone in the drainage basin is unknown (Schütt *et al.,* 2005).

2.6. Land use and land cover

Agriculture is the predominant land use throughout Lake Abaya drainage basin. High percentage of land is devoted to farming except steep rocky hillsides, where the preserved natural vegetation cover has been suffering from clearance by cutting and burning (Makin *et al.,* 1975; Grove, *et al.*, 1975). The strong altitudinal gradient is reflected a rapid ecological change from *qolla* growing below 1500 m a.s.l., through *woina dega* growing between 1500–2500 m a.s.l to *dega* growing above 2500 m a.s.l. This strong altitudinal dependency of plant growth ensures that plant growth conditions are extremely varied within a small area (Jackson, 1971). The land use system in the highlands is dominated by small-scale subsistence agriculture that integrates livestock, mainly small stock (Thiemann, 2006). South of Hosaina to Sodo, west of Bilate River, and in the Gamo Highlands, the plateau of rolling hills and isolated green valleys is charaterized by groves of *enset edulis* clustered around each compound (Jackson, 1971; Halcrow and Partners, 1992). East of the Bilate River, intensive maize production grades into open grassland, shrubland and woodland (Halcrow and Partners, 1992).

The lowlands, receiving less than 500 mm of annual rainfall, are thinly populated and devoted to cattle-rearing except where highland rivers debouch on the plains surrounding Lake Abaya (Jackson, 1971). Here open and dense bushland occurs mixed with banana, sweet potatoes, maize, dryland cotton and sorghum, grown on fan deposits and often irrigated applying simple techniques (Jackson, 1971; Halcrow and Partners, 1992; Assefa, 2001). Use of tributary rivers for Irrigation has been fairly practiced for private and state owned farms in the lowland around the lake (Bekele, 2001). The valley floor north of Lake Abaya is characterized by open and dense bushland (Jackson, 1971; Halcrow and Partners, 1992). Towards the eastern divide as the land rises, intensively cultivated arable farm land occurs, with coffee, fruits and enset been cultivated merges with disturbed upland forest.

The vegetation varies from open *Acacia* woodland in the neighbourhood of the lakes, now extensively overgrazed, with tall forest trees on the shoulders of the rift, to large areas of grassland on the plateaus between 2000 and 2500 m, and heaths, tussock grass and tropical alpine vegetation on the high mountains (Grove, *et al.*, 1975; Woldu and Tadesse, 1990; Valett-Coulomb *et al.*, 2001). Lake shores partly carry a dense vegetation of the shrubs (*Aeschynomene elaphraxylon*), a light wood of which floats and used to make transport boats (locally known as “hogolo”) (Schröder, 1984). In the flooded zones spreads a more or less broad reed belt of *Typha, Phragnites, Juncus* and *Scirpus*, which merges into the community of submerged vegetation of *Potamogeton pectinatus, P.nodosus* and *Ceratophyllum* (Schröder, 1984). Overall, forest represents a rather insignificant and declining proportion of the drainage area (Makin *et al.,* 1975).