6. Discussion

6.1. Meteorology

6.1.1. The wind field

Analysis of wind records from two stations adjacent to the western shoreline of Lake Abaya shows that a periodic diurnal wind dominates the wind field during 53 days considered. They indicate that the western shoreline experiences a lake breeze during the day and a land wind at night. The daily occurrence of land-and-lake breeze observed in diurnal variation of wind speed and direction suggests that there were relatively light prevailing large scale synoptic flows (i.e., the western shoreline is more or less protected from the general flow pattern). The lake-breeze at both stations found to begin early in the days considered, suggesting that the general flow is reinforcing the lake-breeze (Freizzola and Fisher, 1963).

Comparisons of the time of onset of formation and speed are not in agreement at both stations. The inhomogeneous characteristic of the surface boundary layer is responsible to many of the variations in the thermal forcing involved (Kusuda and Alpert, 1983). The difference in the time of lake-breeze onset between the Fura station in the south and the Wajifo station in the north can be explained in terms of horizontal advection of diurnally cooled air by the large-scale flow (Neumann, 1977). The time of occurrence of lake-breeze at Fura is about one hour earlier than the corresponding time of occurrence at Wajifo. This time difference may represent approximately the amount of time needed for the cold air to move from south to north by prevailing southerly general flow.

The differences in the maximum wind speeds observed at both stations can be accounted for by the broadness of the valley floor and water body and surrounding topography (Fisher, 1960; Kusuda and Alpert, 1983). Comparison of the wind field at two stations showed that the wind speed at Wajifo was usually greater than that at Fura, which indicates greater thermal forcing and less friction (Zhong and Takle, 1992).

The rapid rise of the average diurnal wind speed between 0700 hr and 1000 hr and relatively steady values between 1200 hr and 1600 hr clearly delineate the onset and duration of the lake-breeze (Figure 5.3). Larger speed changes, usually occurring in short periods in the morning and in late afternoon, are probably associated with the onset and cessation of convective mixing (Crawford and Hudson, 1973). The maximum speed observed during the daytime can be explained by the pronounced vertical exchange of momentum during early afternoon because of thermal convection (Yu and Warner, 1970). The near stagnations of early morning and nighttime points represent approaches to two equilibriums (Staney, 1957). Weak lake-breeze suggests that the stations are located far from appreciable reinforcing by mesoscale forcing of the nighttime mountain winds (Kusuda and Alpert, 1983).

The resultant wind direction is found to oscillate and the average rate of rotation at both stations is far from uniform over the diurnal cycle (Figures 5.4 and 5.5). The common feature at both stations was relatively rapid rotation during onset of lake-and-land breeze and a slow turning at later times. Rotation of the wind vector in the lake-land breeze is a result of an imbalance among the Coriolis, mesoscale, and large scale pressure gradients (Zhong and Takle, 1993). Thus, the difference in the rotational rates at any given time from station to station indicates that the forcings responsible for the rotation were not uniformly distributed in either time or space (Zhong and Takle, 1993).

The comparison of simultaneous wind records at Wajifo and Fura stations reveals that there is a spatially variable distribution of wind stress along the western shoreline of Lake Abaya. The difference between wind roses of two stations corresponding to the same month emphasizes the impact of the shape of the shoreline and local topography on the wind field distribution around the lake (Figures 5.6 and 5.7). On the other hand, similarities and differences between monthly wind roses at a station mark the presence of characteristic seasonal pattern.

The prevailing large-scale synoptic flow has a direct effect on the strength of the lake breeze (Johnson and O'Briens, 1973). The calmest month at Wajifo (January) is in the dry season of the suppressing northeasterly synoptic-scale winds prevailing in most of the East Africa, whereas the strongest month (June) with predominantly southerly component is in the rainy season when the southeasterly general wind pattern is more active (Figures 5.8 and 5.9). Further, the directional change of the lake breeze is slowed down during the rainy season when the lake breeze and general wind are on the same direction (Neumann, 1977). At Fura, winds during the rainy months consist of a variety of synoptic conditions that include winds from many directions (Figure 5.7). These suggest that the effect of large scale synoptic wind system on the lake-and-land breeze is more propounded in the larger and more exposed north basin than the south basin.

Wind records of 2 and 5 minutes intervals at Wajifo and Fura stations were processed to form mean monthly winds for a one year period (March 2004 – February 2005). Mean annual winds are then formed for both station by averaging all the monthly means. The annual mean winds at both stations are similar. The annual mean winds contain contributions from harmonics of diurnal cycle, but these should generally cancel in vector summations and should generally be small in comparison to the general flow pattern. These mean quantities, however, must be used with care since the wind direction distribution oscillates diurnally. The monthly and annually averaged winds at both stations suggest that the prevailing southerlies would dominate lake water circulation and associated material distribution. However, it is obvious in the original data that many of the strongest winds come from the east. These strong winds are likely to have major effect on the sediment dispersal in the transverse direction.

6.1.2. Temperature

The average diurnal variations of surface air temperature shown in Figure 5.11 by the monthly mean values of each hour of a day at Wajifo station can be attributed mainly to the absorption of solar energy (Pernter, 1914; Balland, 1933). It is apparent in the graphs of average diurnal surface air temperature march that rainy season (June – September) is characterized by fairly uniform increase in temperature after sunrise. The relatively rapid rise in air temperature between 0600 hr and 0800 hr local time in the dry season is probably brought about mainly by the relatively small amount of water vapour before the lake breeze develops fully. This rapid increase in smoothened during rainy season by relatively great amounts of water vapour available from moist soil and vegetation. The tendency of uniform and slow rise to the daily peak afterwards throughout the year suggests that the lake breeze along the western shoreline produces important effects on the diurnal variation of the air temperature.

Seasonal differences in temperature pattern occur between rainy season (June-August) and dry season at Wajifo weather station. Both, standard deviation and mean daily temperature range are larger in dry season. This might be due to the water vapour in the air, which decreases the diurnal range by decreasing the maximum temperature and increasing the minimum temperature (Balland, 1933; Court, 1951). The maximum temperature in rainy season is decreased largely (1) by the depletion of solar energy in passing through water vapour, and (2) by the evaporation of surface moisture. The minimum is increased by the absorption of ground radiation.

The effect of incoming radiation and the more instable state of the atmosphere in the early morning around onset of the lake breeze could make the wider primary modes of the frequency distribution of warming. The changes from the generally observed primary modes of the daily average interdiurnal variability could be steered by the general circulation and not by local factors. On the other hand, the seasonal characteristics of interdiurnal variability do not appear to be certain, because of the material here considered in this study is not extensive enough.

6.1.3. Atmospheric pressure

Roden (1965) noted that the atmospheric pressure oscillation can be regarded as consisting of two parts: the regular oscillations due to the atmospheric tides, and the irregular oscillations superimposed upon them. Several investigators (e.g. Pyle, 1959) described the mechanism which links the 24-hr component to the daily heating and cooling. The primary diurnal minima in the afternoon near the time of maximum heating are explained by the fact that the daytime heating causes the air to expand upwards and also outwards into regions of less heating. The outward expansion results in a depletion of mass from the air column and thus causes the pressure to fall slightly at valley bottom stations. On the other hand, the primary maxima are caused by the nighttime cooling and contraction that cause a corresponding pressure maximum near the dawn. It is therefore observed that there is a close agreement between observed diurnal minima and maxima and hours of maximum heating and cooling. The highest daily pressure ranges of 117.62 mb on 1 June 2004 and the lowest daily range of 4.14 mb on 10 August 2004 occurred in rainy months when the atmospheric pressure system is active.

6.2. Sedimentology

6.2.1. Texture

The textural trends observed in Lake Abaya may assist the interpretation of the transport and deposition of sediments relative to increasing or decreasing energy environments due to wave and current activity. It is well known that sediments maintain the essential characteristics of the source material modified by the agents of transportation with its final texture and composition reflecting the overall conditions existing at its point of deposition (Thomas *et al.,* 1972; Yuretich, 1979; Håkanson, 1981). Overall, surficial sediments from the north basin of Lake Abaya comprise the coarser (sandy) fines in large proportion, whereas samples from the south basin are composed mainly of silt and clay. This general pattern of the lake sediments' textural distribution is a direct function of different energy environments. It suggests that relatively higher energy environment exists in the northern basin due to relatively stronger wind stress and hydrological flow pattern (Figures 2.3 and 5.6) and shallow water depth (Figure 5.13) (Thomas *et al.,* 1972; Håkanson, 1977).

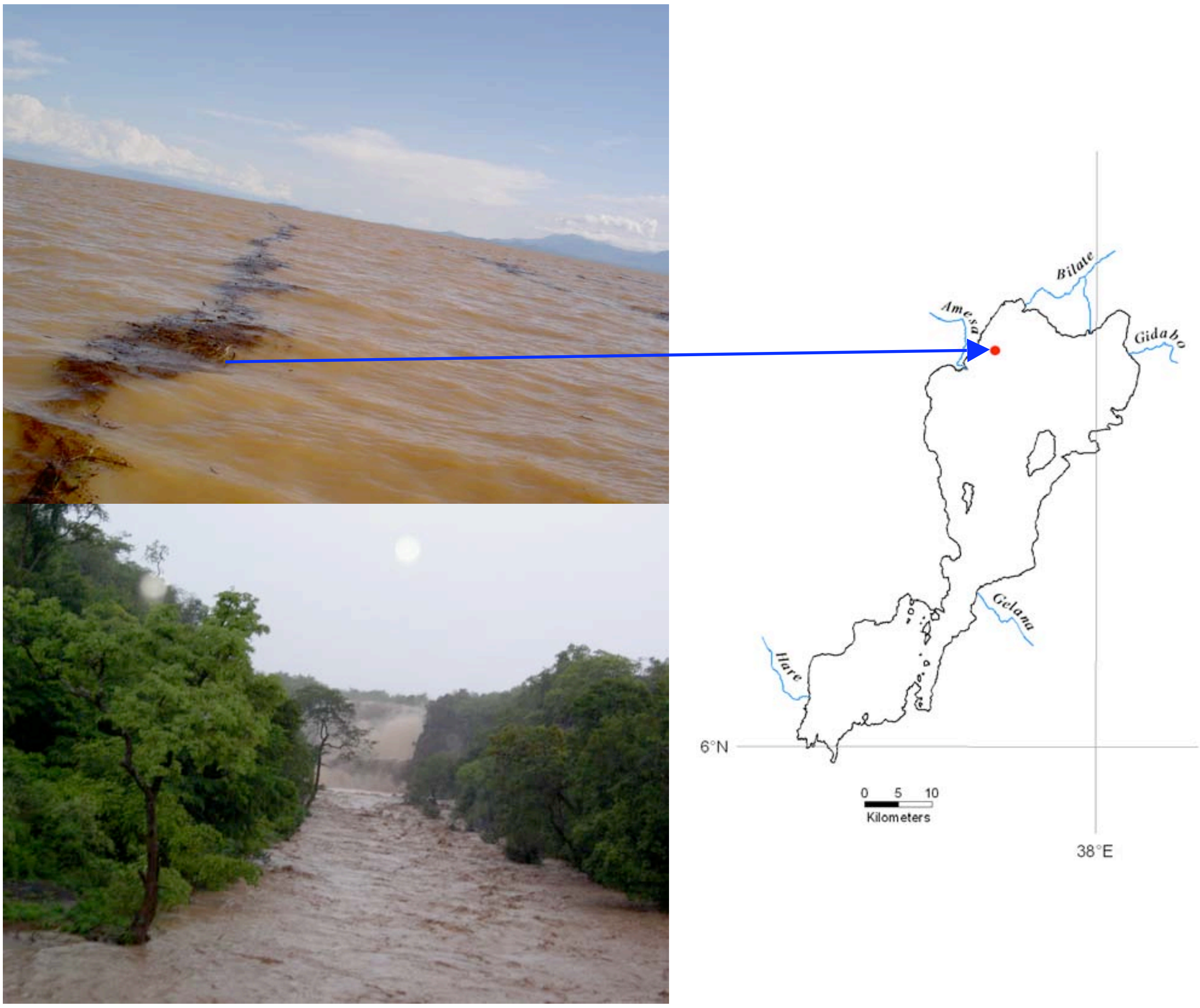

Figure 6.1. (Left top): sharp river plume on 1 May 2004 extending about 10km from Bilate River mouth; (left bottom): Amesa River flooding on 30 April 2004.

No sample was found entirely free of silt and clay fractions. The occurrence of fine materials in small amount at the deltas of major streams provided evidence that sediment settles from suspension when the inflow energy decreases. Dispersal which is caused by mechanical agitation near the stream mouths and shallow regions prevent deposition of fines (Wright, 1995; Van Maren and Hoekstra, 2005). Correspondingly, it appears that the great bulk of sand sized erosion products remain as foreset beds and topset beds at the deltas. Increase in clay fraction offshore and downstream from river inputs is explained by the fact that deposition of fines probably occurs shortly after flocculation has overcome dispersal, so that progressively more flocculated material is deposited as water speed decreases (Holmes, 1968).

The prime cause of grain size variations of Lake Abaya lake floor sediments is water depth which, in turn, is a function of distance from shoreline. Lake floor sediments characterized by high silt and clay fraction predominate in water depths >5 m throughout the lake. Thus nearshore zone, there is a progressive deepening of the lake leading to decrease in sand and an associated increase in clay. In the deeper part of the lake the sediments consist almost entirely of fines with a minimum of discrete sand. High-energy conditions at main river mouths following flood events (Figure 6.1) would perhaps have caused more energy transmitted from river mouths to deep water carrying small fraction of sand. Most sediment is brought into the lake by floods which could be expanded several kilometres from main stream mouths during the heavy floods in rainy seasons. Sharply defined paths of the river plumes extending for kilometres from the mouth of Bilate River were observed during the field work (Figure 6.1), which suggests that outflow inertia dominates the dispersal pattern of effluent during large runoff events (Wright, 1977).

6.2.2. Mineral composition

Quartz

Basin of Lake Abaya can be divided into distinct regions with respect to the quartz content of lake floor sediments (Figure 5.15). Samples with relatively large quartz contents (>15 vol. %) are confined to comparatively narrow areas along the shoreline. This suggests that most of the quartz introduced from upland drainage is deposited in the deltas of the major rivers and dispersed along the shore. The north end of Lake Abaya close to the mouth of Bilate and Gidabo rivers is characterized by high contents of quartz with respect to the central and south basin, which can be attributed to the high quartz contents of the detrital load of both rivers. As quartz predominantly occurs in sand and silt fraction and originates from the drainage basin, its deposition concentrates on the delta regions. Correspondingly, the increase in quartz content at deltas is related to natural sorting during sedimentation with quartz content deposited at any locality being the net result of both the suspended load and the characteristics of the transporting mechanism (Thamas, 1968).

Feldspar

Also origin of feldspar in lake sediments is from the drainage basin, documented in its linear correlation to the quartz contents. Highest percentage of feldspar at deltas in the north and west of Lake Abaya suggests that feldspar is like quartz abundant in detrital loads of tributaries originating from the Western Highlands. Similarly, locally increased feldspar concentrations at the southern end of the south basin reflect the increased importance of the frequent inflow of Kulfo and Hare rivers during rainy seasons.

Clay

The abundance of clay minerals in lake floor sediments of Lake Abaya suggests that detrital loads of streams contain high percentage of fines in clay fraction. The sheltering effect of hilly surroundings to wind-induced lake circulation results in low energy zones that favour clay minerals to settle from suspension. On the other hand, funnelling effect at the narrow passages between islands and bottleneck connection may form high-energy zones, which prevent deposition of clay particles. The southward increasing clay concentrations can be explained by increased turbulence due to wind-induced waves and currents which slow down deposition of clay fraction from suspension.

Calcite

Analysis of mineral composition shows that carbonates in the lake floor sediments only occur as calcites, while Mg-calcites and dolomites lack. As carbonates lack in the drainage basin (Schütt *et al.,* 2005), the carbonates in lake floor deposits are derived from precipitation form the lake water and (or) deposition of organisms (shells, bones). The small calcite contents in most sediment samples and relatively uniform distribution in the main basin imply that calcite precipitation occurs area wide in the lake basin. On the other hand, the influence of local source areas is indicated by higher concentrations in certain near-shore localities. For example, the abundance of snail shells in the sediments from sites close to the eastern shoreline suggests that most of the calcite removal is accomplished biologically.

Organic carbon

The low contents of organic carbon in most sediment samples reflect well mixed, oxidizing environment of the overlying water mass encouraging bacterial decomposition of organics (Yuretich, 1979). Since the organic matter in water is present in true solution, in colloidal solution, and as a suspension of organic detritus and living organisms, each of these forms plays different part in the supply of organic matter to sediments (Bordovskiy, 1965a, 1965b). In mountain rivers the proportion of organic matter totals 4–5% of the mineral salts in solution, and the greater part is detritus (Bordovskiy, 1965b). This general fact suggests that low organic carbon contents in the lake floor deposits of the main basin can be partly explained by the small fraction of dissolved organic matter to be extracted by adsorption of suspended mineral particles and its incorporation in bottom deposits. Another reason for low organic carbon in the deposits of the lake's central zone can be attributed to the attack of detritus-feeders and bacteria during sedimentation of the organic detritus (Bordovskiy, 1965b). Organic carbon contents are increased around river mouths corresponding to organic detritus washed in with runoff. Next to this, increased concentrations of organic carbon at near shore zones can be related to increased population of habitants such as hippos and crocodiles and human activities.

Interrelationship between variables

The direct relationship between concentration of clay in lake deposits and water depth suggest different energy environments. Variations in clay content can be attributed to variations in the degree of mixing causing decreasing energy as water depth increases as discussed previously. The inverse relationships between water depth and lake sediment's quartz contents and feldspar contents respectively can be explained by the transport mechanisms of suspended fines corresponding to grain size as discussed above (Thomas, 1969).

Although the relationship of the organic carbon content to clay content in the lake sediments is that organic carbon increases with increasing clay content (e.g. Thomas, 1969; Schoettle and Friedman, 1973; Hilton and Gibbs, 1985), it may be influenced by environmental conditions. For example, carbon loss may be incurred through oxidation during settling and (or) deposition in well oxidized bottom sediments (Thomas, 1969). This is evidenced by the fact that the reddish-brown sediment colour at the water sediment interface indicates oxidizing conditions (Thomas *et al.,* 1972; Schoettle and Friedman, 1973). Sediments containing high organic carbon content are black, indicating reducing conditions (Schoettle and Friedman, 1973).

The differences of the average mineral compositions at river deltas can be directly related to the petrological character of the source areas (Figure 5.23). Because the Western Highlands are the source area for the rivers entering Lake Abaya from the west and north, sediments of the corresponding deltas possess a strong compositional resemblance. Similarly, the compositional character of sediments in the eastern deltas is closely controlled by the detrital load of the main tributaries.

Lack of clear trend in mineral composition along the transverse axis of the lake from west to east can be explained by nearly flat bottom topography of the main basin. The abrupt increase in depth near shore zone causes a sudden drop in energy level, which allows deposition of most of the fine load from suspension, resulting in a sharp change in depositional characteristics. Exception to this is that the sheltering effect of the surrounding hilly topography from wind forcing creates low energy zone to give rise to identical compositional trend near shore and main depositional zones.

Cluster analysis

The geographical relevance of each cluster is inferred by comparing mean values of the mineralogical contents in the identified clusters (Figure 5.25). Samples included in Cluster 2 from North Basin with quartz content above average and located mostly offshore suggest that strong circulation in the north basin resulted effective dispersal of quartz fraction in sediment input mainly during flood events. The most variable minerals across clusters (i.e. feldspar and clay) could explain different energy zones prevailing in Lake Abaya, with higher feldspar or lower clay value corresponding to higher energy zone. The Clusters 1, 2, 5 and 6 with highest mean proportion of other minerals, which included samples mainly from deltas and near-shore localities, indicate that localized compositional character of sediments is closely controlled by the detrial load.

6.3. Water Quality

Significant changes in water quality with water depth of Lake Abaya were not observed during the study period. Lake responses to the wind forcing were documented by the vertical mixing of the water column as indicated by total suspended solids (TSS) concentration levels and profiles of water quality parameters. Lack of significant stratification effects for different variables are indicators of continuous mixing, initiated by wind driven wave motions in the environment of Lake Abaya. Olango and Odada (1996) note that the water column of Lake Turkana is particularly well mixed above 15 m depth as a result of wind induced surface waves, with subsurface counter currents generating further mix the rest of the lake water at depth. Several other studies on the mixing of East African tropical lakes (Eccles, 1974; Spigel and Coulter; 1996; Bugendyi and Magumba, 1996; Ochumba, 1996; Halfman, 1996) show that the stratification patterns possess well defined mixed layers ranging from approximately 60 up to 200 m depending on season. These depths extend far beyond the maximum depth of Lake Abaya and suggest that the light winds predominating for the most part of a day on Lake Abaya are sufficient enough to generate waves that will keep the top layer well mixed so that fines will remain in suspension.

Secchi depth distribution

The attenuation of light in water is a function of the interaction of size-concentration-composition of suspended material as well as the effect of dissolved substance (Biggs, 1970). Thus, loss of water clarity in Lake Abaya, which was reflected in the lower Secchi disk depth, is due to both, high solids in suspension and high colour due to dissolved solids. Sources of suspended solids are external (introduced by freshwater run-off), marginal (shoreline erosion), or internal (supply of organic matter and skeletal material from primary production within the system) (Biggs, 1970; Halfman, 1996). Each of the input processes may operate according to a seasonal cycle, so that, at any time during the year one of these processes may dominate over the others. The effect of the Omo River sediment plume on light attenuation in Lake Turkana, with somewhat comparable sediment source mainly from the western part of Lake Abaya drainage basin, is found to be dramatic (Spigel and Coulter, 1996). This may suggests that the relative contribution of suspended sediment to light attenuation in Lake Abaya is high.

Suspended solids

Resuspension of bed sediments by current and wave action can contribute to the turbidity at shallow depth but this factor was probably of minor importance as significant differences in Secchi disk depth between shallow and deep portions of the lake lack. In the shallow areas of the lake, upward decreasing TSS stratification is due to gravitational settling of sediments and mobilization of bottom sediments. Particulates subject to gravitational settling are expected to accumulate towards the bottom. This does not explain the substantial and more frequent decline of TSS concentration in the lower water layers at deeper stations. It is more likely that the amount of fine material moving within the lake in the top layer is a significant fraction of the sediment that is deposited on the lake bed. High concentration of TSS near surface following the rainy periods implies that most of the sediment input by the tributaries consists of fine grain particles (Håkanson and Jansson, 1983). Thus, the fineness of the clay together with the high dissolved solids content of the water account for the persistent turbidity of Lake Abaya.

The association of TSS with average flows is evident in two respects: the geographical distribution of TSS, with higher concentrations near stations affected by major tributaries, and a tendency for declining in TSS concentration during low average flows. An increased TSS concentration in October 2004 typically is due to sediment-rich floodwater. On the other hand, the southward tendency of TSS is explained by two trends: higher concentration of TSS at station S5 in the south direction than at station S6 in the north, and generally similar average TSS concentration variations between stations S5 in the north basin and S4 at the centre of the north basin. Significantly higher concentrations of TSS or lower Secchi transparency occasionally at station S1 in the south end of Lake Abaya most likely reflect flood flow from Kulfo River, which leaves its main channel draining to Lake Chamo and enters Lake Abaya at the south end during flood events (Schütt and Thiemann, 2006).

Dissolved oxygen

Factors potentially contributing to the oxygen budget of the lake water include primary algal photosynthesis and respiration, reaeration from the atmosphere (i.e. mixing), advection, biochemical and sediment oxygen demand, and nitrification (Wood and Talling, 1988; Losada, 2001). Nearly uniform dissolved oxygen levels with depth at all fixed stations suggest that oxygen demands created by different components of the oxygen budget were offset by enhanced productivity by the algal community and reaeration from the atmosphere via wave activity and mixing process. On the other hand, slight fluctuation of dissolved oxygen only near surface water is indicative of the inherent relationship between dissolved oxygen and temperature; oxygen is more soluble in cold water than in warm water (Camp and Meserve, 1974). Thus, surface aeration can act as either a source or a sink of oxygen depending on the temperature and oxygen concentration of the surface layer (Losada, 2001).

Conductivity

Electric conductivity of water is a function of water temperature and the total number of dissolved ions in water (Bartram and Ballance, 1996). The overall spatial and temporal structures of the average electrical conductivity at fixed stations indicate that both freshwater inflow and evaporation play a major role in the salt budget of Lake Abaya. A decline in average conductivity at stations close to the mouths of major tributaries during high discharges might be due to dilution with freshwater with less dissolved ions, whereas an increase in conductivity levels during dry months is more likely due to the low inflow and higher irradiance, and hence increase surface water loss by evaporation. The shore line fluctuation at flat surroundings during the course dry period and after major rain events in the catchments indicated the importance of evaporation in the water balance of Lake Abaya.

Other water quality parameters

Most water quality parameters are strongly affected by surface processes (Jones and Bowser, 1978; Ward and Armstrong, 1997). Solar radiation, wind, rainfall and temperature interact within the water mass to determine the structure of the water column (Bugenyi and Magumba, 1996). Fluctuations of water temperature near surface and strong correlation with air temperature are consistent with domination of surface heat flux in the tropical lakes. The vigorous vertical mixing rendered many parameters measured vertically homogeneous. A high degree of aeration is implied by nearly homogenous vertical structure of dissolved oxygen profiles. Observation of deficit dissolved oxygen near bottom at S9 indicates increased oxygen consumption in the water column and in the lake floor sediment. Although electric conductivity is considered technically as a conservative parameter (Ward and Armstrong, 1997), it has been observed to be less conservative most of the time. This can be accounted to the role of evaporation to affect the solute budget of the lake (Sonnenfeld, 1984). The effect of freshwater inflow in depressing electric conductivity is demonstrated at sites close enough to the major tributaries to respond to their inflow. Furthermore, the north-to-south trend of increasing average electric conductivity distribution can be due to decrease in fresh water inflow southwards.

The specific composition of water on any lake will depend upon the length of time that the lake has existed, the volume and composition of the inflows, the rate of evaporation from the lake's surface and the retention time of water in it (Baxter, 2002; Teklemariam, 2005). In general the highest concentrations are found in closed basin or terminal lakes, in which the retention time approaches infinity (Baxter, 2002; Legesse *et al*., 2004; Alemayehu *et al.*, 2006). The dissolved solids and pH are normally high in Lake Abaya due to the geological characteristics of the basin area that is underlain during the tertiary and quaternary periods of basaltic formations and the dominance of the calcium-magnesium-bicarbonates contains of tributary rivers (Teklemariam, 2005).