RECENT MONITORING OF SUSPENDED SEDIMENT STRESS, BULK WATER QUALITY PARAMETERS AND METEOROLOGICAL FORCING ON LAKE ABAYA

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Abstract

Lake Abaya is the largest lake of the Main Ethiopian Rift Valley. Distribution pattern of lake bottom sediments is reflecting the interaction of physical processes and the resultant motion controls the transport and distribution of suspended solids. As well the inflow current of the tributary rivers as wind driven wave energies have an important influence on the spatial distribution of sediments.

Wind energy continuously mixes the lake water and transports sediment in suspension. Sediments found on the lake bottom are mainly composed of fines in the silt-clay range in the deep and central area, and in sand-silt-clay range in the shallow areas close to the shorelines. The field research was conducted to understand the variations of water quality parameters and sediment distribution on the lake bottom and to identify processes influencing them.

Key Words: Lake Abaya, sediment transport, wind, water quality

1 Introduction

The interaction of physical processes, both forcing and response, and the resultant motion, control the transport and distribution of sediments in Lake Abaya. Both, the inflow current of the tributary rivers and wind driven wave energies, are important for the distribution of sediments. They are deposited on the lake bottom and remaining in the water column in suspension.
Their significance is evident in the water columns and lake bottom sediments at the deep and central areas of the lake that are at remote locations from the mouths of major tributary rivers.

Sediments found on the lake bottom are mainly composed of fines in the silt-clay fraction in the deep and central area, and in sand-silt-clay fraction in the shallow areas close to the shorelines.
Wind energy continuously mixes and transports sediment in suspension. Thus, the Total Suspended Solids (TSS) concentration is generally high even with little new sediment input during dry seasons.

The Field research was conducted to understand the variations of water quality parameters and distribution of lake bottom sediments, and to identify the processes influencing them. Because wind generated waves mix water vertically and transports horizontally, the knowledge of the wind field is critical in understanding water circulation and associated material transport and, finally, spatial distribution.
The aim of the field research was to investigate processes influencing lake functioning using comprehensive observations.

2 The Study Site

Abaya is large shallow lake with an area of about 1140 km^2 and a mean depth 8.6 m (Bekele 2001), situated in the southern part of the Ethiopian Rift Valley (Figure 1). The lake is oriented in the north-south direction, and has maximum length and width about 79 and 27 km, respectively.
It is the largest of eight Ethiopian Rift Valley Lakes and the second largest lake in the country. Lake Abaya consists two main basins connected with a bottle neck-like transition. The larger north-basin is characterized by a slightly rolling morphology, less structured with islands, and flat surrounding topography and hence more exposed to wind.

The south-basin is structured by chain of islands, and the surrounding topography is mainly hilly in the south and east directions. The hilly shorelines in the west of the north-basin and south and east of the south-basin are rocky. The outflow at the south end is blocked since 1997-98. As a result, the Lake Abaya became a close system with sediment trap efficiency of 100 percent.

Geologically the Lake Abaya basin to the south is surrounded by extensive Nazarth group outcrop, which forms to the east and west the main Ethiopian plateau areas. To the north, a sequence of contemporaneous and post-Nazareth volcanics forms the dominant rock types in the basin (Mohr 1961). The formation extends from the valley floor from Lake Abaya northwards through much of the valley slopes and escarpments to the highland boundaries.

Lake Abaya receives most of its sediment loading from the tributaries around the lake during rainy season, while Bilate River in the north of the basin, which is the major tributary and highly turbid through the year (Schütt et al. 2002, in press, Schütt & Thiemann 2004). The main land use in the catchments includes agriculture and cattle rising (Getahun 1978, Westphal 1975). Soil erosion from croplands is therefore the major source of sediment load to Lake Abaya (Krause et al. 2004, cf. Lal 1990).

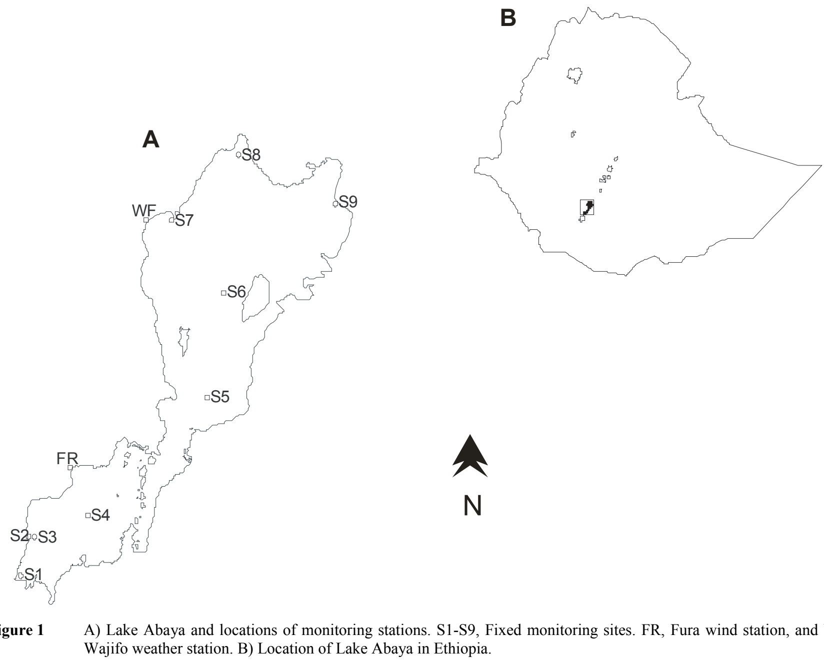

Figure 1 A) Lake Abaya and locations of monitoring stations. S1-S9, Fixed monitoring sites. FR, Fura wind station, and WF, Wajifo weather station. B) Location of Lake Abaya in Ethiopia.

3 Methods

Field surveys were made in Lake Abaya between 2003 and 2004. The main dataset consists of meteorological records from two stations at the western shoreline and water quality data from nine stations indicated in Figure 1.

3.1 Meteorological data

Two meteorological stations at Fura (FR) and Wajifo stations (WF) were established for this study right at the west shore of the lake. The Fura station in the south records wind data, whereas the Wajifo station records wind data along with air temperature, global radiation, air pressure and rainfall.

The stations are situated to the west of the longest transverse lengths and around the middle of the main basins in the south and north. The flat topography of the surroundings at both sites is suitable to capture wind information from any direction.

The data were recorded as either two or five minute averages since February, 2004. Hourly averages of the nine months period from February through October, 2004 were derived from them to use in the present analysis.
Although the available data set is not sufficient for formal statistical analysis to investigate the spatial distribution of winds around the lake during events, it provides important information to compare local wind fields between stations.

3.2 Water quality data

The main water quality data set consists of records of depth profiles of the water temperature, pH, dissolved oxygen (DO), electric conductivity, and total suspended solid (TSS) concentration measurements. Water quality parameters were monitored using a SEBA HYDROMETRIE portable Water Quality Multiprobe.

Water samples for laboratory analysis were collected from nine fixed monitoring sites (Figure 1) on a regular basis: nearly bimonthly and monthly from four fixed stations in the south basin and five stations in the north basin, respectively, using depth-integrated manual sampler of SEBA make.

The stations in the south basin are located in the southern part near the abandoned natural overflow (site S1), close to the mouth of the major tributary in the south basin (site S2), about 1 km to the east from mouth of Hare River (site S3), and around the center of the south basin (site S4). Similarly, the locations of the five sites in the north basin are close enough to the mouths of the major tributaries, and to the southern and central parts. Depths of sampling were near surface, 2m intervals, and 0.5m and 1m above the lake bottom.

TSS concentration was measured by filtering a known volume of the water sample and by differential weighing of the dried filters. Other water quality parameters were measured along depth profiles and generally consisted of near surface measurements and subsequent measurements at 1 m intervals when maximum depth is >3m or 0.5m interval. Otherwise, with the final measurement being at 0.5 m from the bottom during each water sampling sessions. Additional vertical profiles were recorded during preliminary survey in the south basin along transects defined from east to west in September and October, 2003.

4 Results

4.1 Meteorological data

The persistent light winds coming from west and strong winds from southeast occurred continuously from February to October 2004 at Wajifo. Variable winds prevailed at Fura, but the persistent northwesterly winds occurred during all months. Daily wind cycles were characterized by diurnal land-sea breeze across the shore lines that were produced by a temperature gradient between the land and the lake.

Monthly data of the first time records at the western shoreline stations for each month were considered separately for detailed investigation of the characteristics of wind field variations.
The corresponding monthly wind roses for the nine month period from February, 2004 to October, 2004 reveal that the winds at both stations showed seasonal characteristics. From February to April and in August, westerly winds were predominant at Wajifo, while winds from northwest occurred predominantly from February through May and between September and October at Fura.

From May through July and between September and October, southeasterly winds were predominant at Wajifo, whereas southwesterly winds prevailed at Fura from June through August. Winds from southwest were equally important at both sites in May. At Fura winds either from southwest or from northwest appeared to be equally important in August. Wind from northeast was very rare at Wajifo.

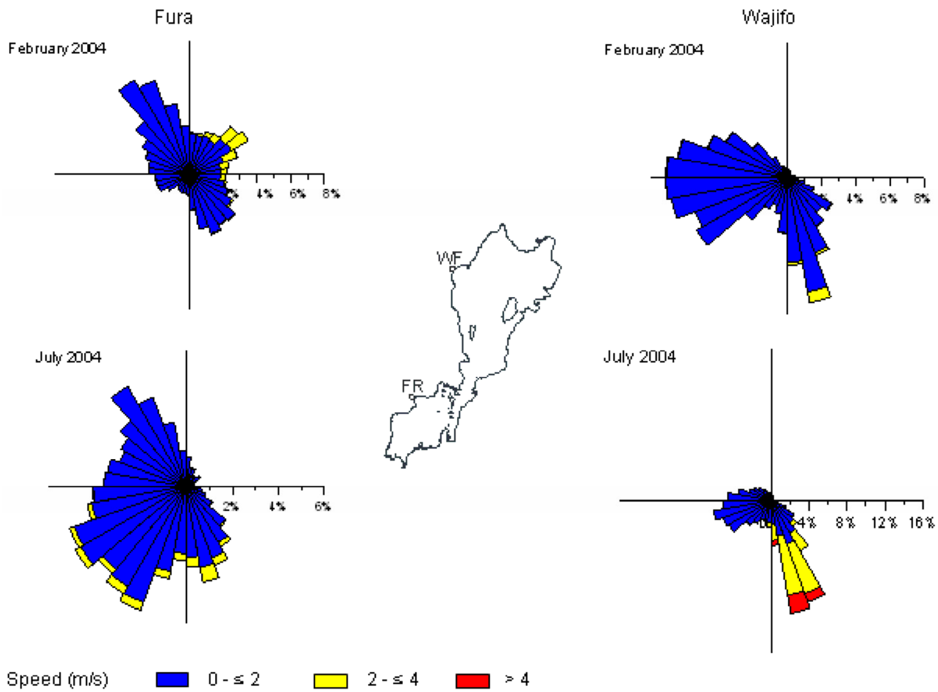

Figure 2 Typical monthly rose diagrams of the winds at the Wajifo and Fura Stations. Winds are shown "coming from".

The wind characteristics in terms of variations in strength are analyzed using monthly wind records at Fura and Wajifo stations from February to October, 2004 as shown in Figure 3.
The speed class histograms for monthly wind records revealed that winds at WF generally appear stronger. The lighter winds of speed < 2 m/s occurred more predominantly at Fura (for about 92-98% of nine months period) than at Wajifo, where the monthly frequency of occurrences ranged 61-98%.

At Wajifo the calmest month was February, whereas the stronger winds with speed > 4 m/s appeared during the months of May to July for 4-10% of the time.

The maximum winds recorded at Fura (6.4 m/s) and Wajifo (9.1 m/s) in May and September, respectively. The maximum wind speed is the greatest of 5 minutes average records. Because the wind speed at both sites very through a range of time scales of recording from 2 to 5 minutes, the actual maximum wind speed that occurred during the recorded nine months period may not have been captured although it would not be expected to differ greatly from the measurements.

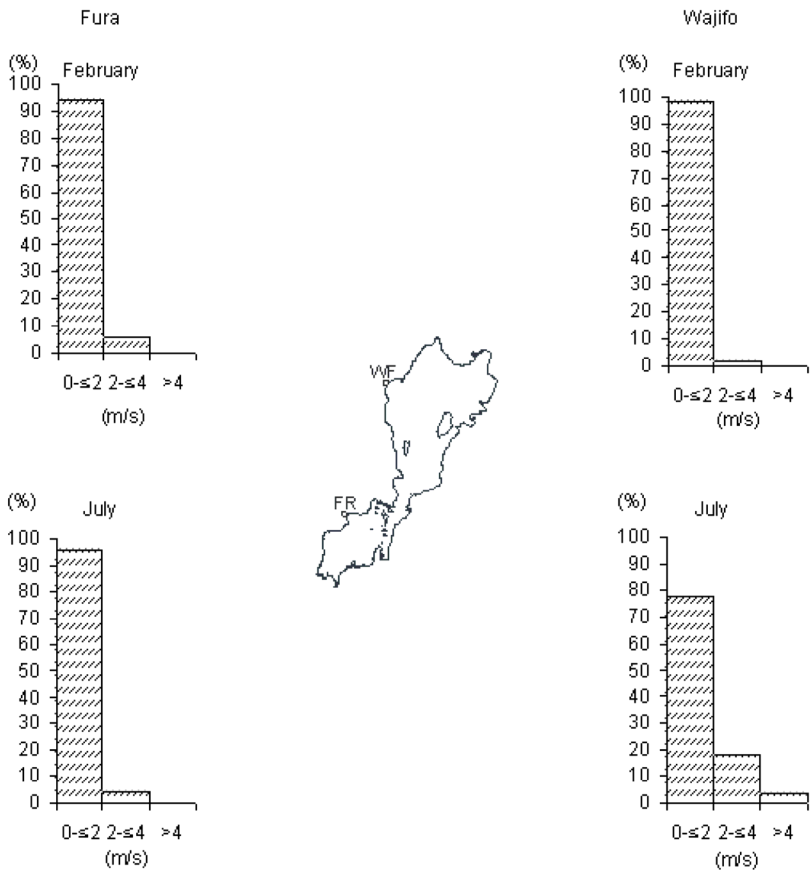

Figure 3 Typical speed class histograms of monthly wind speeds at Fura and Wajifo.

Diurnal wind field dynamics is observed in more detail by computing mean vectors for each hour of a day to reduce perturbations due to large scale events to a level that is acceptable for the envisaged variations.
Two ranges were considered to investigate the general wind patterns observed in the monthly wind rose diagrams. The wind vector distribution for the hourly averages of 53 days (from 7th of February to 30th of March, 2004) records of 2 minutes average shown in Figure 4.

The variation of the diurnal wind pattern is identical at stations situated in the west shoreline. Nearly parallel wind vectors oriented across the shore at both stations revealed that the diurnal wind pattern is well developed along the western shore. The onshore sea breeze commences in the morning and lasts for 8-9 hours.

The daytime maxima at both sites are much greater than the nocturnal maxima. It is also observed that the land breeze during the night is weak at both stations. The see-breeze at full scale and the daytime maximum occurred early at Fura. The nocturnal maximum at Wajifo is greater than at Fura, whereas the daytime maximum at Fura is greater than at Wajifo.

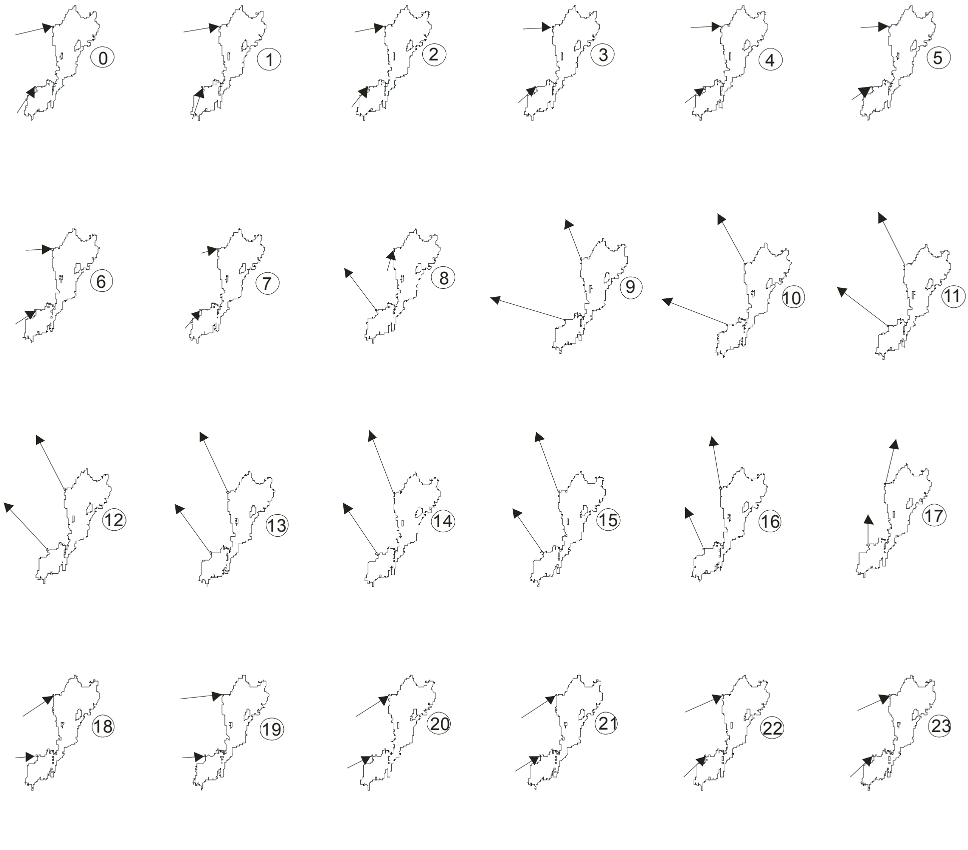

Figure 4 A typical wind along the west shoreline. Hourly mean wind vectors are derived by averaging reading for each hour of a day over 53 days (2 min. average records from 7th of February through 30th of March). The corresponding hour of each diagram is circled.

4.2 Water quality data

The water quality data set is categorized into two sets of parameters: field measurements and laboratory analysis. Depth profiles of both data sets were analyzed for the minimum, maximum, average and median values of each parameter for all stations and monitoring depths.

The data coverage is sporadic at sites S8 and S9 in the north basin because of bad weather, and at site S2 in the south basin due to disturbance by aggressive hippos. Spatial unevenness appears for the near-bottom quality parameters due to the fluctuation of maximum depth at fixed stations. Since measurements at each stations were made only once during sampling day, they did not capture the daily variation and extremes of water quality parameters.

Dissolved Oxygen

The content of dissolved oxygen in the lake water is mostly in the range of 6-7.8mg/l. An overall analysis of the depth profile reveals that a large percentage of the data is made up of concentration of dissolved oxygen (DO) greater than 6.5 mg/l.
Concentrations less than 6.5mg/l did not appear before August at site S1, or even not before October at other stations. The vertical stratification is rare and slight, average on the order of 0.1ppm/m.
Vertical variation in dissolved oxygen was insignificant; a relatively slight stratification in DO increasing upward observed in deep water. There is no apparent correlation with depth in stratification, although low DO events occur primarily in the measurements at depth. Occasional profiles show uniform DO throughout the depth. General trend of slightly declining DO concentration occurred starting July, 2004.

pH

The depth-profiles of pH show that conditions of constant values at all sites extend throughout the water column. Much of the measured dataset for pH has a value of 8.9, and the variation was very little within a range of 8.8-9.1 over the period of observations.

Temperature

The vertical structure of the temperature profiles indicates that stratification effects are insignificant, amounting on average to a fraction of a degree per meter positive upward. However, rise of up to 5°C close to the surface observed during warm weather and calm wind condition.
Water temperature near surface and near bed can be very different (21.9-30°C). The near-surface variations are confined to the top layer of about 2m thick. Horizontal spatial structure is virtually absent except for the near-surface layer. Relatively low temperatures were measured in June and July months at all sites, which account for seasonal signal.

Conductivity

The depth profiles structure of conductivity is obscured because of relative constancy in conductivity. The average conductivity distribution is predominantly a north-to-south gradient of increasing conductivity. The effect of freshwater inflow in depressing conductivity is demonstrated at sites close enough to the major tributaries to respond to their inflow. Time trends in conductivity in general show very slight increase with time at the sites remote from freshwater inflows.

Suspended Solids

Suspended solids in Lake Abaya on the average range 10-400 mg/l throughout all fixed monitoring stations, higher in sites influenced by freshwater inflow. Stratification in TSS is usually noisy, especially at sites located in the deeper central parts. The depth profiles of TSS at shallow sites close to the major tributaries in the north basin found to be nearly homogenous.

Interestingly, high concentrations of TSS in the top 2m layer and low concentrations near bed were observed frequently in the deeper central parts of both south and north basin.
The median concentrations of TSS at the sites around the center (S4 and S6, respectively) are found to be 37 mg/l and 49 mg/l near surface, 38 mg/l and 66 mg/l at 2 m depth, 16 mg/l and 58 mg/l at 10m and 8m depths. The measured values at S4 and S6, respectively, are in the range 14-96 mg/l and 13-138 mg/l near surface, 13-79 mg/l and 12-137 mg/l at 2m depth, and 10-79 mg/l and 10-151 mg/l at 10 and 8m depths.
The general spatial trend of TSS concentrations is decreasing towards the center. The highest TSS concentration are found at S9, which is located close to the mouth of Gidabo River.

Secchi Disk Depth

Lake Abaya has extremely low clarity with Secchi disk depth average of 13 cm (range 5 – 22cm). Loss of water clarity, which was reflected in the lower Secchi disk depth, was due to both high color and high solids.
The difference in Secchi disk readings between shallow sites, which are close to the river mouths and shorelines, and central deep parts of the lake during sampling dates has been less than 5 cm. The higher Secchi depth was found at sites located in the deep and central part of the lake.

5 Interactions of Physical Processes

In order to provide qualitative understanding and background of the lake water circulation patterns, the vertical profiles of water quality parameters at fixed stations are compared to the wind events during the field sessions.
The comparisons of prevailing daytime winds at Wajifo station with the depth profiles of water quality parameters at fixed monitoring stations in the north basin indicated that wind generated waves might have played a significant role to maintain higher TSS concentrations in the top layer of the water column in the central and deep part of the lake. The concurrent occurrence of lower concentrations of TSS 1m above the lake bottom explained continuous mixing of the top layer and fine sediments of light weight had no chance to settle to the bottom.

Both, the strength and duration of wind events determine the level of mixing of water column vertically (Håkanson & Jansson 1983). This is demonstrated by the occurrences of two circumstances. The strong wind on April 18 for the most part of the day time and till 20 hrs mixed completely the water column as evidenced from profile measurements on April 19, where the wind has moderate strength. On the other hand, moderate vertical mixing after relatively strong day time wind on August 20 indicated the significance of the duration of the stronger wind for complete mixing.

The occurrence of high TSS concentrations at S6, in the central part of the north basin, in August and September did follow up to various flood events in the drainage basin and indicates hydraulic transport of suspended fines inside the lake basin (Lerman 1979).
The persistent winds from the west and southeast are expected to move the water in their corresponding directions. Thus wind forcing might be responsible for the distribution of sediment in the transverse directions.

6 Discussion

The analysis of the nine months wind records from two stations situated in the west shore revealed that the wind field structure varied with location over the period of observations. The persistent light winds at both stations across the shorelines indicate that diurnal winds are important components of the general wind field along the shoreline.
The variations in the diurnal wind field at both stations could be due to the effect of the local topography. The small difference in the strength of the nocturnal winds might be because of the small temperature gradient between the land and the lake during night (cf. Griffith 1972).
Lake responses to the wind forcing were documented by the vertical mixing of the water column as indicated by TSS concentration levels and profiles of water quality parameters. Complete mixing needed strong wind

with longer duration event. The light winds are sufficient enough to generate waves that will keep the thin top layer well mixed so that the fine sediments will remain in suspension (Lerman 1979).

In the shallow areas of the lake, TSS stratification decreasing upward, could be due to both, the gravitational settling of sediments and mobilization of bottom sediments. High concentration of TSS near surface following the rainy periods implies that much of the sediment input by the tributaries consists of fine grain particles (Håkanson & Jansson 1983).

Most water quality parameters are strongly affected by surface processes (Berner 1971, Jones & Bowser 1978). The vigorous vertical mixing rendered many variables vertically homogeneous. A high degree of aeration is implied by nearly homogenous vertical structure of DO profiles.
Observation of deficit DO near bottom at S9 indicated more oxygen consumption in the water column and in the bottom sediment. Differences in temperature measurements that appear to be spatial because of change in near surface value from one site to another can easily be temporal due to the time taken to travel between the two sites.
Although conductivity is considered technically as a conservative parameter, it has been observed to be less conservative most of the time (Gizaw 1996). This could be accounted to the role of evaporation to affect the solute budget of the lake (Sonnenfeld 1984).
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.

7 Conclusions

It is shown that winds at the western shoreline showed directional preference and characteristic daily patters. All dominant winds at Wajifo station winds showed stronger directional preference than at Furo station. Variations in the general wind fields at both stations adjacent to the western shoreline could be accounted to the effect of surrounding topography. The wind fields at two stations in the western shoreline are variable, both temporally and spatially. This suggests an incomplete understanding of the wind fields around the lake.

All dominant winds at Wajifo and Fura stations are of light to moderate strength, and the onset of rarely occurring strong winds were sudden. Therefore, it can be conclude that the light winds of diurnal structure are important for the circulation of the water and for maintenance of very fine particles in suspension. The degree of vertical mixing is a function of both, the strength and duration of the wind field.

In general, the Lake Abaya water is characterized by high temperature, high dissolved oxygen contents, high alkalinity, very low visibility, electric conductivity around 1000 µS, and high solids in suspension. The most significant water quality problem of Lake Abaya is associated with high TSS concentrations throughout the lake basin. The remarkable feature of TSS in Lake Abaya by this study is the persistent high TSS concentrations near the surface.

There is limitation inherent in using less than 1 year data record to examine inter-annual variability. Therefore, it is emphasized that monitoring from existing fixed monitoring stations must be continued for a minimum of several years to allow for trend analysis.

8 Acknowledgements

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