7. Conclusions and Recommendations

The main subject of this thesis is estimation of the mean circulation pattern in Lake Abaya based on the spatial and temporal variability of physical parameters and sediment distribution. A one-year observation of meteorological forcing along the western shoreline suggested that land and lake breezes are important components of the prevailing wind system. The diurnal wind variations have essentially the same feature at both weather stations established at Fura in the south basin and Wajifo in the north basin. During a typical sunny day, the lake surface is calm in the morning, with winds picking up between midmorning and noon, strengthening in the afternoon and dying out in the evening. Diurnal variation of wind speed and direction was in about the same time each day, with daytime wind from lake to land being stronger than nighttime wind from land to lake, and stagnations for a short while early in the morning and in the evening. Directional preference and difference in strengths of wind components in opposite direction in diurnal basis considered as important indicators for the existence of mean currents representing large scale circulation.

Lake Abaya presents a number of special features. It mixes throughout its depth during every month of the year. It is shallow (maximum depth 24 m) and the water level fluctuates through the year quite markedly. Its drainage basin has a higher degree of spatial and temporal variability of precipitation. The concentration of precipitation into fewer months is producing greater seasonality of inflow patterns.

The most conspicuous feature of rainy season behaviour of Lake Abaya is the combination of strong winds and high flows with high sediment input into the lake. Large amounts of freshwater and fines are delivered by the tributaries during energetic discharge events. The initial fluvial sediment dispersal is mainly determined by the flow dynamics of the plume, but the subsequent dispersal will be regulated by the mixing rates with ambient water. Major tributaries are expected to cause appreciable horizontal current in the offshore direction in the vicinity of river mouths. Prevailing winds in the north basin during the rainy season are from south-east and north-west, while the stronger winds were always coming from the south-east direction. Higher wind speeds will produce higher current speeds at all depths. The resulting mean circulation patterns are a northward alongshore and southward return flow in the main basin. Consequently, large volumes of water and sediment exchange between the north and south basins can occur after flood events of the main tributaries in the north basin following rainy seasons.

The mean currents in the shallow nearshore zone are relatively stronger than the counterpart mean currents of return flow in the deep central zone. The strong current near shore zone has considerable importance for dispersal of any effluents near shore. Owing to the natural sorting based on the characteristics of suspended load and transporting mechanism, the coarser particles settle near-shore from the water-body, while the finer particles (clay and silt) might remain in suspension for months or years. Thus, still finer particles are transported to the greater depths and southwards from input points located mainly in the north basin, and this is important to explain the horizontal extent of total suspended solids concentrations (TSS).

Southward and offshore, descending into the central basin, net water flow and associated sediment transport is indicated by an increase in TSS at the station around the centre (S6) and further south in the north basin (S5) following a rainy season. The net transport of fines in the shore region may depend on the relative strength of currents induced by alternating onshore and offshore winds on a diurnal basis. Since onshore winds are stronger than offshore wind, currents at the bottom and surface layers are quite strong and opposite in direction than in the case of offshore winds. In consequence suspended sediments are transported away from the shore by the large currents. In general, most of the fluvial sediments are deposited during calm weather and when the weak offshore wind causes insignificant bottom shear stress. These sediments, however, can later be resuspended, owing to the presence of strong onshore wind, and can be transported offshore by the strong currents near the bottom layer. It is, therefore, apparent that repeated accumulation, erosion, and transport results in the long-term transport of sediments from nearshore to the deep portion of the basin.

Lake Abaya floor sediments are dominated by muds, showing little variability over wide areas. Decreasing percent sand (or feldspar and quartz) is negatively correlated with increasing percent of clay. In addition, percent sand decreases and percent clay increases with increasing depth. These mineralogical trends are due to hydrodynamic sorting by high-energy conditions at shallow proximal areas and declining energy as water depths increase at deep distal portions. The rapid energy decrease at stream mouths appears to allow deposition of much of the sand and silt. As the energy level further decreases out into the lake clay particles begin to flocculate and the floccules are deposited alongside the remaining sand and slit. Any major trends in mineralogy at deltas of major tributaries are likely to reflect source variation. Thus this investigation recognizes that mineral sorting trends of lake deposits, containing large amounts of detrital origins, might be used in interpretation of sediment transport patters in shallow lake basins.

Stratification of water quality parameters in a shallow water body like Lake Abaya is generally of low significance. The intense wind mixing together with shallow depth apparently result an essentially homogenous water column. In general, the Lake Abaya water is characterized by high temperature, high dissolved oxygen contents, high alkalinity, very low Secchi disk depth, high electric conductivity, and high concentration of solids in suspension. Sediment loading by river inflow and subsequent transport and mixing would have caused more or less uniform TSS concentrations at the stations close to the river mouths. It appears that the highest TSS concentration following raining months reflects the significance of increased erosion from upland catchments. More frequent occurrences of higher TSS concentrations near surface than near bed in distal portions suggest that most of the suspended load spreads though Lake Abaya as surface overflows and shallow interflows. Continuous and prolonged mixing of the top layer by wind-induced currents and wave action leads to the persistence of clay in suspension. Thus, most of the fine sediments, predominantly clay and fine silts, are distributed by near surface currents.

Conceptual model

Conceptual models describe the physical processes that are part of an environment, how they relate to each other and which processes dominate the system (Flint *et al.*, 2001).

They define the general physical framework within which important components of system dynamics can be captured and details of their processes can be worked out (Flint *et al.*, 2001; Kavetski *et al.*, 2006a). An important, perhaps defining, feature of conceptual models is that their parameters are not directly measurable and must be inferred ('calibrated') from the observed data (e.g. Beven and Binley, 1992; Kavetski *et al.*, 2006a).

The current conceptual model of mean circulation of Lake Abaya water is evolved in order to account for the processes reflected in observed field data as well as for those concepts from relevant literature references that are most consistent with the measured data and observations. Recent observations and past records are relevant to the discussion of the assumed conceptual model for a typical average condition of variables. The major components of the conceptual model address the following processes: (a) inflow of freshwater and sediment; (b) outflow from the lake; (c) mixing of freshwater with ambient water and sediment dispersal; (d) mean wind forcing along the western shoreline; (e) mean circulation pattern, and (f) evaporation from lake body. A simplified schematic that highlights these components is depicted in Figure 7.1. It should be noted that this approach follows descriptions and explanations in the previous chapters, and the suggested conceptual model diagram is not to scale.

A. Freshwater and sediment input at several locations around the lake vary temporally and spatially considerably, ranging from intermittent to large-volume perennial flows depending on the season and catchments characteristics. From spatial and temporal variability of TSS concentration at fixed stations close to the river mouths and mean monthly lake input and rainfall in the drainage basin, it is inferred that lake input processes are governed primarily by the distribution and timing of precipitation in the drainage basin, the physical properties of the surface soils and the processes controlling soil erosion. Lake input is represented by mean values (1970–2003) of volumetric records at gauged main tributaries (Figure 2.6). From mean annual total inflow data, more than 90% input was observed in the north basin that correspond to net flow of water and associated sediment in suspension from north to south. The noticeable increase in Total Suspended Solids (TSS) concentration around the centre of south basin following high flow period in the north basin supports further that significant fraction of water and sediment entering at the north basin transported further to the south basin.

B. Lake Abaya lacks a direct surface outlet and drains into Lake Chamo by overflowing the sill in its south end during lake level highs (Bekele, 2001; Schütt and Thiemann, 2006). With respect to the water budget of Lake Abaya, the average values for the period 1969–1996 of components suggested by Bekele (2001) are: inflow to the lake, 1902 x 10^6 m^3/year; precipitation on the lake, 787 x 10^6 m^3/year; evaporation, 2405 x 10^6 m^3/year; and outflow 115 x 10^6 m^3/year. These values show that all water input is approximately balanced by evaporation, with outflow making minor contributions. The lake water may interact regularly with the near-surface groundwater storage in highly porous deposits in the rift floor around the lake (Makin *et al.,* 1975; Grove, 1986) depending on the seasonal fluctuations of the lake level. Therefore an arrow indicating groundwater recharge or discharge flux could be included in the mean conditions shown in the conceptual model depicted in Figure 7.1, and while deviations from this conceptual model may occur in some instances, this illustration depicts the general mean hydrodynamic response of Lake Abaya to external forcing.

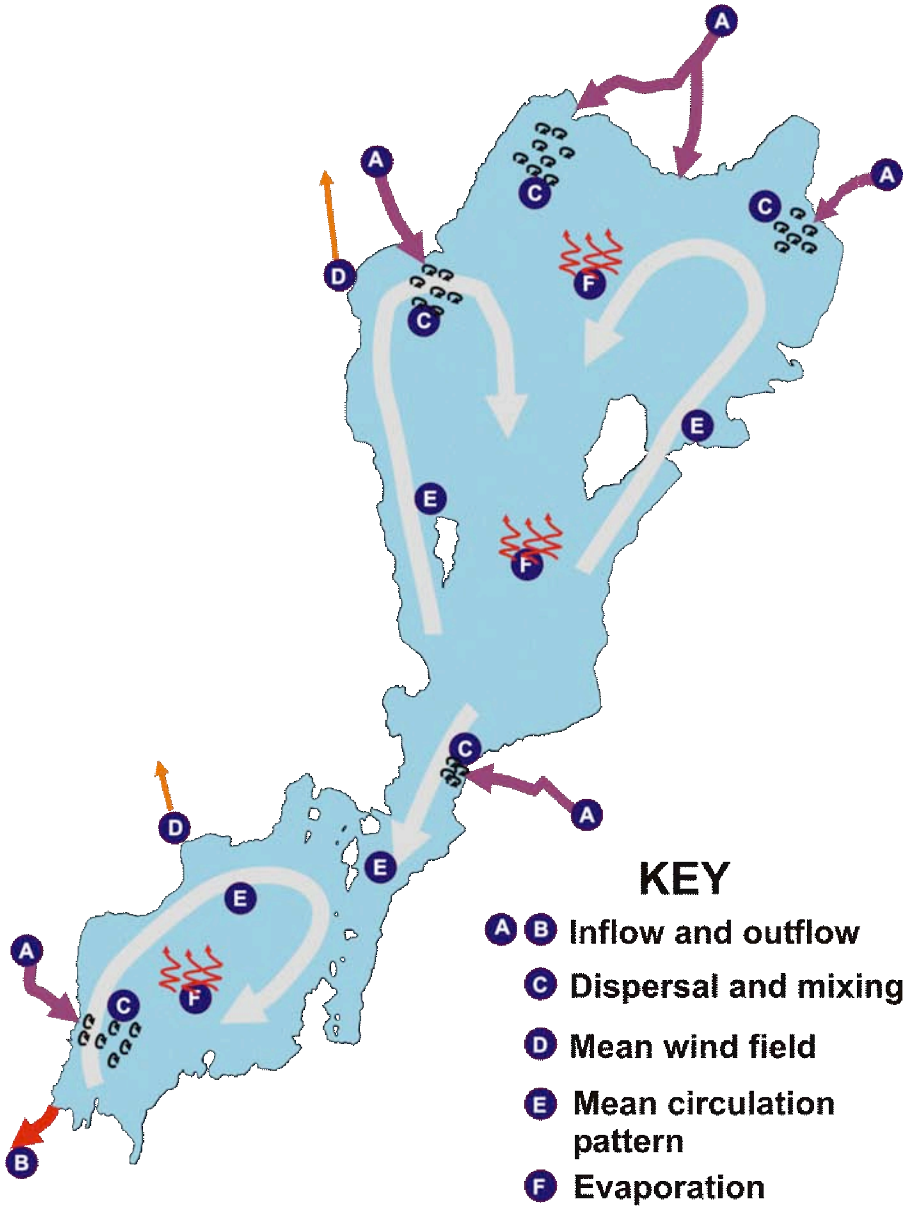

Figure 7.1. Generalized conceptual model of Lake Abaya water circulation. Arrows denote direction of flow and mean wind field, letters denote the major components described in the text.

C. From water column profile of TSS concentration at fixed monitoring stations near the mouth of major rivers, the initial fluvial sediment dispersal is characterized by nearly well mixed water mass during dry season, whereas highly turbid buoyant plume transported offshore during maximum sediment supply for the major part of the rainy season. Additionally, it was observed during 2003–2004 field year that the Bilate River plumes were advected from two entrances at the north end to the south by well-developed coastal currents which originated from the river discharge inertia. Channelling or focused flow occurs during flood events resulting fast flow pathways, which transport sediment input further downstream. These findings confirm the fact that dispersal and mixing of reverine input with lake water will take place depending on the energy transmitted to the lake by stream currents and varying contributions from modifying forces (Garvine and Monk, 1974; Carmack *et al.*, 1979; Blanton and Atkinson, 1983; Wright, 2006). Therefore in strong and rapidly changing currents the effluents will be dispersed more effectively (Murthy, 1972; Hilton *et al.*, 1986). Winds occurring from different directions in Lake Abaya will alter the surface plume as the inertia dissipates and enhance lateral dispersion of fresh water and sediments in the transverse direction (Warrick *et al.,* 2004). Further, textural and mineralogical compositions of surficial sediments obtained from deltas suggest spatial variability of lake input and strength of dispersal mechanisms.

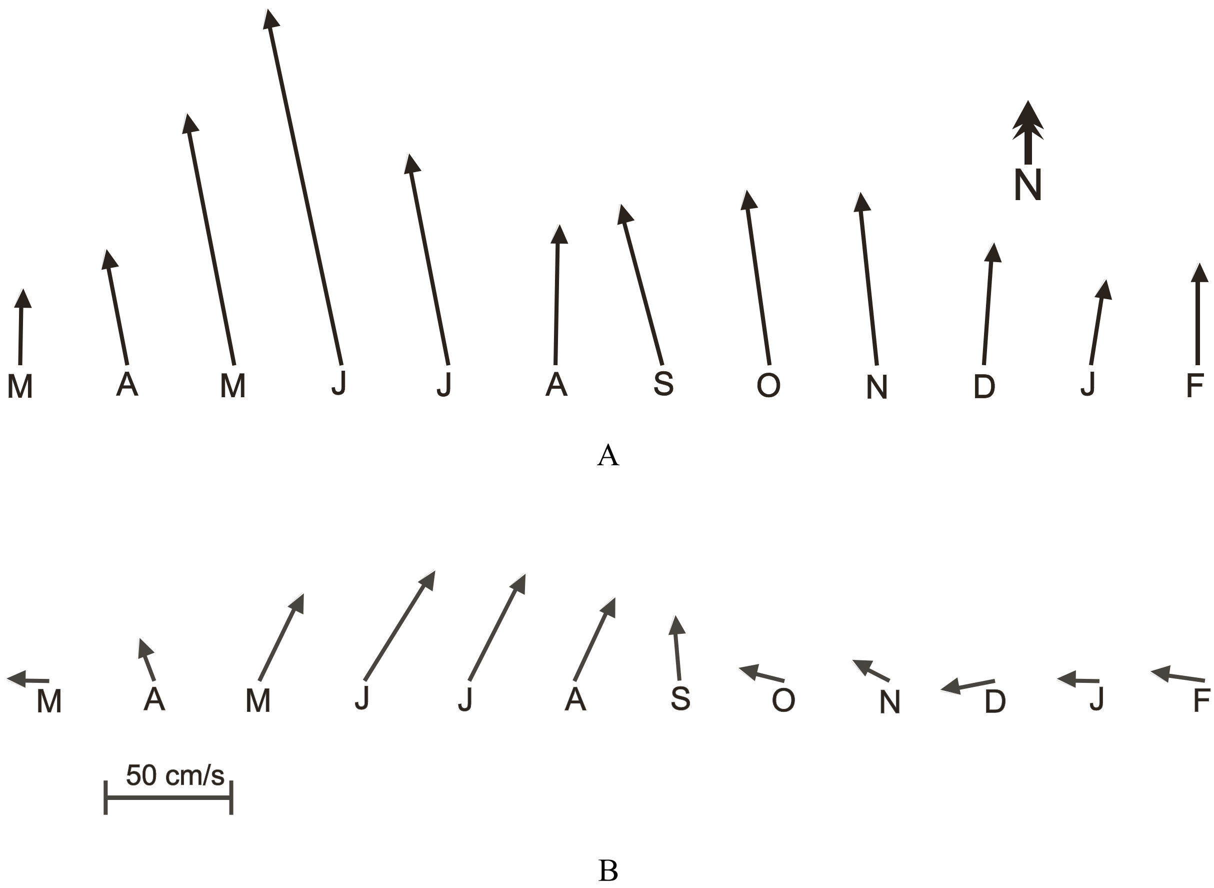

Figure 7.2. Monthly average wind vectors: A, at Wajifo Station; and B, at Fura Station (March 2003 – February 2004)

D. Observations of diurnal wind field along the western shoreline and profiles of water quality parameters at fixed stations during 2003–2004 suggest that wind induced currents and waves are the principal, year-round controls on the strength of water circulation within Lake Abaya. The daytime lake breeze and nighttime land breeze are sufficiently strong to influence the lake's circulation and associated sedimentation processes. The near stagnations of early morning and nighttime points would encourage sedimentation, which could be reworked further by currents and waves generated by alternating onshore and offshore winds.

The monthly averaged wind vectors in Figure 7.2, derived from 2 and 5 minutes records at stations along the western shoreline of Lake Abaya, indicate that strong mean winds are mainly southesterly. Orientation of the major axis of elongated Lake Abaya is parallel to the regularly flowing strong winds in the uplake direction, from which it is inferred that wind forcing in the longitudinal direction plays a key role in transporting the water and sediment in suspension horizontally and mixing them vertically. However, it gets obvious in the weather data that many of the strongest winds come from the east. It is increasingly evident that these strong winds are likely to have major effect on the sediment dispersal in the transverse direction. For example, the widespread existence of quartz fraction in sediments obtained from the deep central zones in the north basin may provide further support for the effectiveness of strong episodic winds in the transverse direction for much stronger dispersal of sediment.

Stronger southerly winds prevail at both stations during the rainy season when peak floods occur. This suggests that the combination of most sediment input and highly energetic conditions of external forcing in the wet season would encourage effective mixing and rapid dispersal, resulting weak TSS concentration gradients between near river mouth and central stations as well as nearly identical temporal trend of water quality parameters at fixed monitoring stations. Overall, the relatively stronger winds in the north basin would result in stronger circulation patterns than in the south, which is illustrated by spatial trend and relative frequency of mineralogical composition of bottom sediments in the two main basins (e.g. Figures 5.15–5.17). Based on reviews of the evidence for various sedimentary processes that have been inferred from seismic reflection and side scan sonar profiles from East African Lakes, Johnson (1996) notes that surface waves generated by strong winds can sort and redistribute sediments in water depths as great as 100 m.

E. The monthly and annually averaged winds along the western shoreline (Figures 7.1 and 7.2) suggest that the prevailing southerlies dominate mean lake water circulation and associated material distribution. Assuming these average wind vectors correspond to the two main basins of Lake Abaya, it is possible to pose the following hypothesis for the wind driven mean circulation in Lake Abaya depicted in Figure 7.1.

The literature suggests a general northward flow of surface waters in response to the southerly winds is accompanied by compensating flow of the lower layers southward (e.g. Gedney and Lick, 1972; Csanady, 1973; Signell *et al.*, 1990). On the average, the northerly mean currents in the nearshore zone will transport water parallel to the shoreline in the direction of the mean wind and the return flow will be downlake to the south in the main basin (Bennett, 1974; Lien and Hoopes, 1978; Pickett, 1980; Hunter and Hearn 1987; Beletsky *et al.*, 1999). The monthly mean wind vectors in the north basin are southerly for every month of the year, with a maximum mean wind run of 122.4 Km/day in June. The resulting mean flow can be two gyre circulations in the north basin (Csanady, 1967; 68; Pickett and Dossett, 1978; Beletsky *et al.*, 1999). Some of the flow, especially near the shoreline, returns northward on the east and west sides and then eastward along the north side of the lake to re-enter the circulation pattern while the remaining water moves into the south basin through the deep channel in the west of Gidicho Island. This general structure is modified by the small passages between islands and at the bottleneck transition as well as the relative strength of the bathymetric-wind curl effects (Pickett, 1977). The hydraulic role of the narrow transitions between islands and the bottle neck connection of two main basins is increased flow rate as a result of reduction in flow width. The steep slope at the near shore zone may enhance lateral transport compared to the essentially flat floored central areas (Hunter and Hearn, 1987). Since major tributaries enter the lake in the north basin, there is a general water transport from north to south supplying mass from surplus region to deficit region. This suggests that the two main basins on the average interact by mean flow from north basin to the south as depicted in Figure 7.1. A general one gyre circulation pattern seems to be developed in the south basin due to more variable winds observed in the western shoreline (Figures 5.7 and 7.2) and the sheltering effect of the mostly hilly surrounding in the eastern boundary (Csanady, 1968; Beletsky *et al.*, 1999).

F. Lake Abaya loses water presumably by evaporation. The most significant component of water balance of Lake Abaya (about 2.25 m/year or 2405 x 10^6 m^3/year) (Bekele, 2001) is lost to the atmosphere by way of evaporation driven by extensive heating. The seasonal fluctuation in lake level is 0.2 – 1.69 m (Bekele, 2001). As noted by Sigel and Coulter (1996), the large proportion of rainfall and evaporation in the balance of the African Lakes makes their levels particularly sensitive to climate change. This is evidenced further in Lake Abaya by large fluctuation of shorelines at zones of relatively gentle slopes observed during the field work program in 2003–2004. These observations suggest that evaporation during dry season exceeds temporarily the amount of freshwater input.

Limitations

It should be noted that no systematic measurements of currents has been conducted to construct the mean circulation pattern assumed for Lake Abaya. The conceptual model presented in this study is preliminary in nature. It is intended to be the starting point for analysis of Lake Abaya circulation and do not reduce the critical importance of careful measurements and theoretical study for better understanding. Therefore further investigation by current measurements is necessary for direct evidence of the circulation pattern. Overall, it is intended that the suggested simplified conceptual model should be continually evolve and be improved through both theoretical and observational testing and review.

Since the wind field observed simultaneously at two stations along the western shoreline is found to vary considerably, further research on the Lake Abaya land-lake breeze can profit by supplementary wind observations along the north and east boundary.

There is limitation inherent in using less than one year data record to examine inter-annual variability of water quality parameters. Therefore it is emphasized that monitoring from fixed monitoring stations must be continued for a minimum of several years to allow for trend analysis. Furthermore, large effort must be placed on the establishment of monitoring systems in an attempt to understand the physics of Lake Abaya.