1 Hydraulic Conditions

1.1 Objectives

The objectives of the studies of the hydraulic conditions in Lake Victoria are defined in the TOR:

"To measure patterns of water circulation in selected parts of the lake in order to determine the interaction between the vertical and horizontal circulation components as well as develop simulation models of the dynamics of nutrients, phytoplankton, benthic biota, suspended sediments and dissolved pollutants."

The "selected parts of the lake" were defined as Winam Gulf / Rusinga Channel, Mwanza Gulf and Murchison and Pilkington Bays. The hydraulic retention periods of these areas should also be established.

During the contract negotiations it was agreed that the circulation patterns in the lake as a whole should also be addressed.

The Consultant's task was to advise and assist the WQ Component staff in achieving the above objectives.

1.2 Constraints

The study of the hydraulic conditions was to be based on three activities and data sets:

1. Measurements of vertical water temperature profiles at the lake monitoring stations.

2. Measurements of vertical current profiles at the lake monitoring stations.

3. Calibration and application of the Lake Victoria 3D Hydraulic Framework model to study the horizontal and vertical circulations and determine the retention periods.

The measurements of temperature profiles were made and are analysed in this chapter.

Unfortunately, only the Ugandan team had an ADCP (Acoustic Doppler Current Profiler) at their disposal and were able to measure current profiles at their stations. The data is analysed in this chapter. A simple manual instrument was available in Kenya, but the results were not useable.

The Consultant requested LVEMP to send staff to training courses in Delft, Netherlands on the 3D physical hydraulic phenomena and the use of the model. The training was postponed until Phase II of LVEMP, and it was thereafter not practically possible to use the model for an extensive study.

In view of the above constraints, it was not possible to complete the study of the hydraulic conditions. Some conclusions can be made on the basis of the available data, but a full understanding of the horizontal and vertical circulations must wait.

1.3 Hydraulic Phenomena and Driving Forces

Reference is made to standard limnological text books for the description of the hydraulic phenomena and driving forces in lakes. In this report the phenomena are simply listed and their importance for Lake Victoria is considered.

1.3.1 Thermal Stratification

Thermal stratification is almost always the most important physical phenomenon in lakes, including Lake Victoria. It affects the vertical circulations and the mixing depth, and consequently the vertical stratification of the ecosystem. In Lake Victoria the thermal stratification is weak with a maximum of 2 °C between surface and bed, compared with 10 °C or more in temperate regions. The weak stratification allows easy vertical mixing, which occurs several time each year.

1.3.2 Surface Wind Waves

The wind climate over the lake is gentle to moderate, with maximum wind speeds during storms rarely exceeding 15 m/s. The waves generated by the wind are correspondingly low, with maximum (1 in 100 year) significant wave heights of 2.5 m. The daily waves generated by the onshore-offshore breezes will normally not exceed 1 m. The waves will cause mixing of the surface waters of Lake Victoria to depths of 5-15 m.

1.3.3 Surface Seiches

Seiching is a resonance phenomena like the oscillation of water back-and-forth in a bath tub. It can occur on Lake Victoria during strong wind events that cover most of the lake. A half-wave oscillation mode across the lake would have a period of 5-6 hours. Similarly, a quarter-wave mode of oscillation in Winam Gulf (node in Rusinga Channel) would have a period of 4-5 hours. There are not any reports of seiching in Lake Victoria, but, after data loggers are established on the new water level recorders, the data could be spectrally analysed for the oscillations. Seiching is unlikely to be important for the circulations in Lake Victoria.

1.3.4 Internal Seiches

If a thermocline developed over most of the lake area, it is possible that internal seiching could occur. Internal seiching is a phenomena where the thermocline or interface oscillates in the same way as the surface, and causes intensified vertical mixing and upwelling at the shores. In the unlikely event of it occurring in Lake Victoria, it would have a period of about 1 month. It is not considered to be important for the circulations in the lake.

1.3.5 Wind Generated Horizontal Circulations

Wind generates horizontal circulations in a lake due to both the uneven wind speed and direction over the lake, and the varying water depth. This phenomena is expected to be important for Lake Victoria.

1.3.6 Wind Generated Vertical Circulations

A constant wind blowing for several days across Lake Victoria (eg the South-east Trades) will cause the surface water to move from east to west. This will, in turn, cause a return current from west to east in the deeper layers, and the phenomena is expected to be important for the vertical circulations and vertical mixing.

1.3.7 Langmuir Circulations

Streaks of foam form on the water surface during strong winds. Such streaks are the visual evidence of Langmuir circulations that are vertical helical currents in the upper layer. They are one of the primary ways in which turbulence is transported downward and the upper layers of water are mixed. For Lake Victoria, the mixing will be limited to the top few meters.

1.3.8 River Inflows

The water entering Lake Victoria from the rivers can have a temperature that is different from the lake itself near the mouth. If the river water is warmer (less dense), it will spread out over the top of the lake water. It it is colder, it will sink to the bed and spread out under the lake water. It the lake is stratified, the river water may sink to the level of the interface and spread out there. Under all circumstances, this phenomena will be restricted to the immediate vicinity of the river mouth, ie. a few kilometers. For the Kagera, it might be felt up to 5 km from the mouth. It will not be important for the overall circulation patterns in the lake.

1.3.9 Coriolis Forces

The Equator passes through Lake Victoria, so none of the phenomena due to Coriolis forces will exist, eg. Kelvin waves, Ekman spirals and rotating seiches.

1.4 Methods

With the limited data available, the study methods were restricted to quality checking of the data, graphical presentation and analysis based mainly on visual examination and comparison with previous studies.

The original intention was to rely heavily on the Lake Victoria 3D hydraulic model, but this was not possible for reasons described above. In the future it should be possible to use the model for a detailed study of the horizontal and vertical circulations, the spreading of nutrients and other pollutants, and to determine the degree of reduction of pollutant loadings in order to maintain a "healthy" lake.

1.5 Thermal Stratification in Lake Victoria

Vertical temperature profiles were measured at the stations shown in Figure 1.1 during the lake monitoring cruises.

The analysis of the vertical temperature profile data has been made in two ways:

- An analysis of the development of the vertical profile at each station during the year, ie the time series of vertical profiles at each station.

- An analysis of the vertical profile along a number of transects across the lake, ie. an instantaneous picture of the vertical temperature structure of the lake.

1.5.1 Time Series of Temperature Profiles

The time series of the temperature profiles at a selection of stations are illustrated and discussed in this section. The stations cover the full area of the lake from north to south, and east to west.

Station UP2 - Bugaia Is.
A station at the 60 m depth contour near Bugaia Is. has been used by many Lake Victoria researchers as the "standard offshore station" for all their studies. It has been taken as an indicator of the general condition of the entire lake.

Figure 1.2 is reproduced from Talling (1966) and shows the development of the temperature profile at Bugaia Is during 1960-61. Talling described the development in three phases:

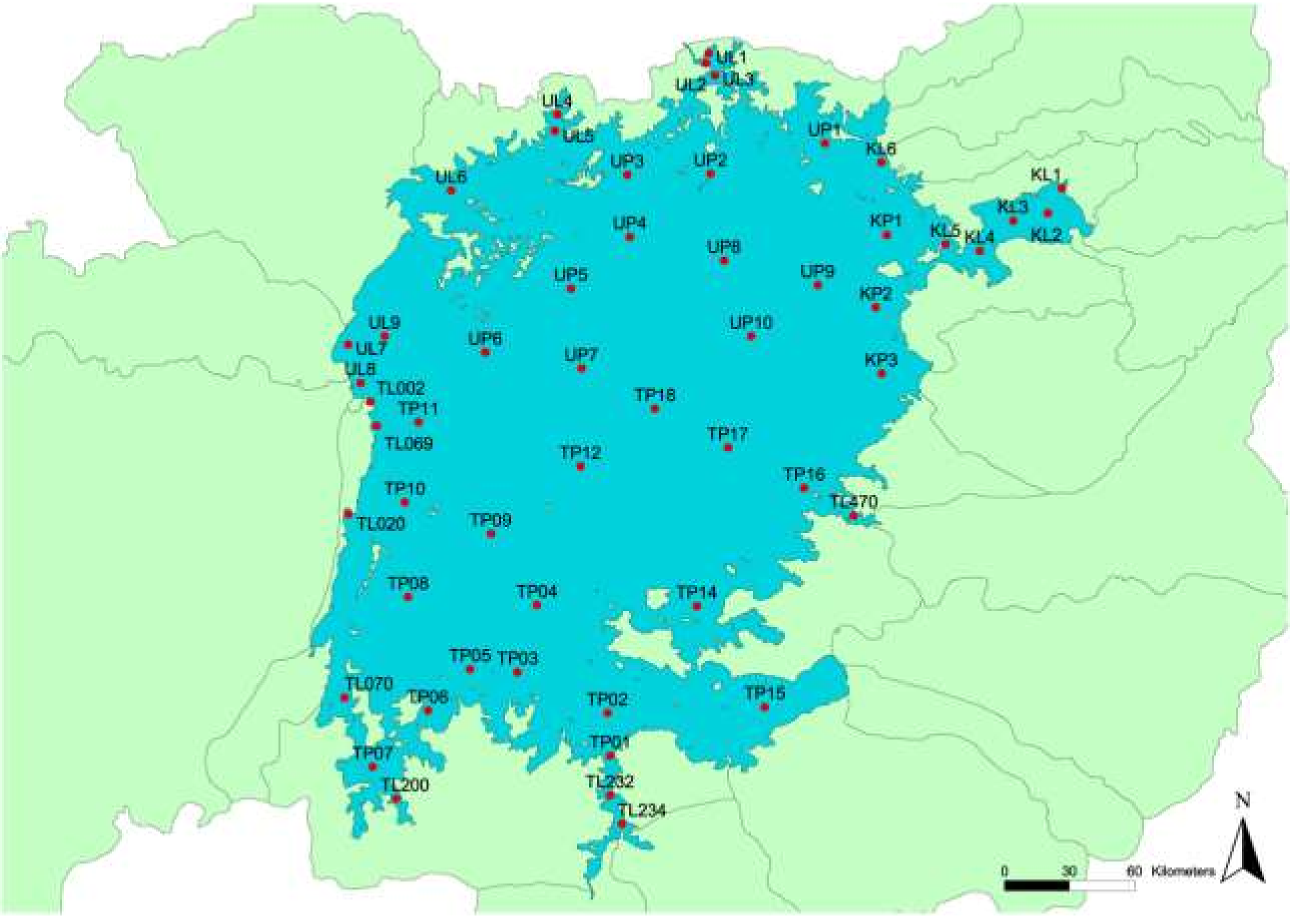

Figure 1.1 Lake Monitoring Stations

Phase 1: September to December. There is a gradual warming of the water column, with heat slowly dispersing from the surface to the bed. There are no strong thermoclines, but more a gradual decrease in temperature from the surface downwards.

Phase 2: January to May. A thermocline develops at depths between 30 and 60 m. It was absent on two occasions, perhaps due to the tilting of the interface across the lake so that the surface waters occupied the full depth. The surface temperature reaches a maximum in March, after which cooling starts.

Phase 3: June to August. Cooling and complete mixing of the water column occurs.

Other measurements by Fish (1957) and Newell (1960) indicate that full mixing can also occur in January, and there is quite some speculation about whether this is due to oscillations of the interface across the lake.

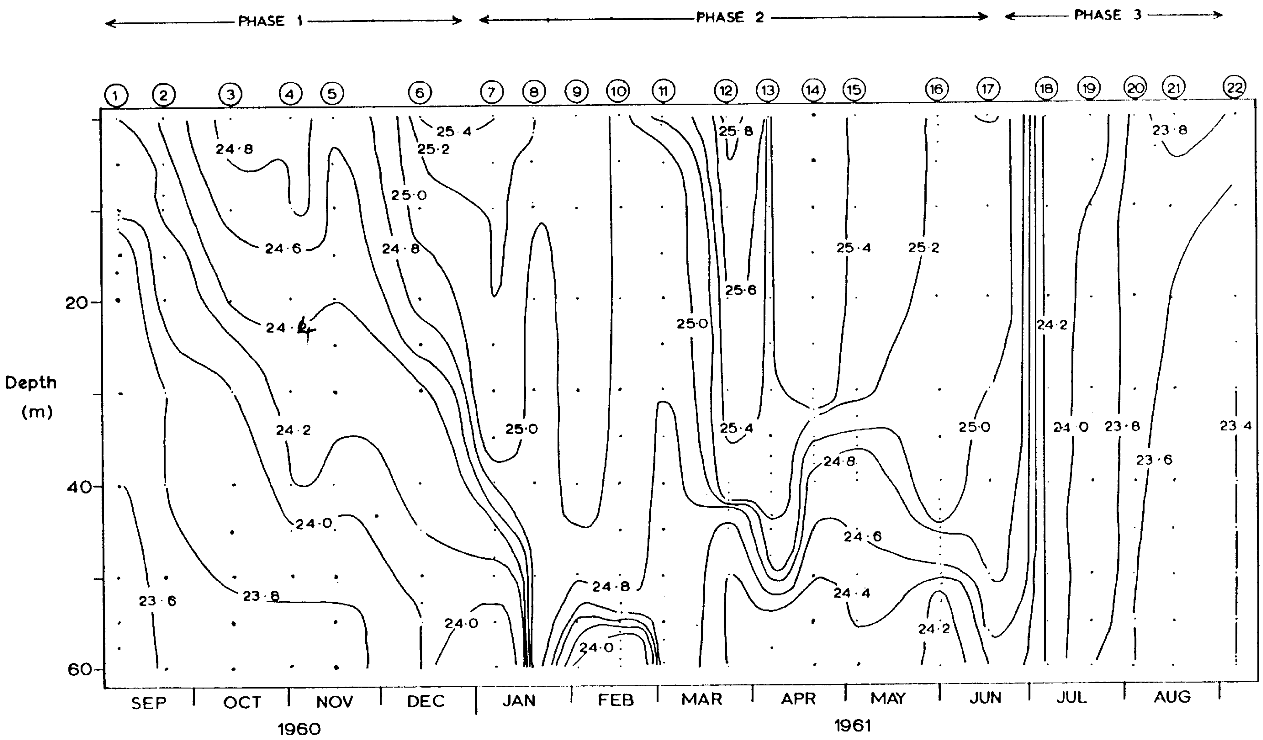

Figure 1.2 Time series of temperature profiles at Bugaia Is. (UP2) 1960-61. Reproduced from Talling (1966).

The temperature profiles measured in the present study are shown in Figure 1.3. Comparing with Figure 1.2, it is seen that the general pattern of temperature changes is similar. There is a gradual warming and weak stratification of the profile at the end of 2000, followed by the development of a strong stratification in January 2001 starting at the surface and moving downward. Cooling and total mixing occurs in June and remains right through to September.

Station UP6

In contrast to UP2, the period of stratification at UP6 on the western side of the lake (Figure 1.4) is limited to February to May when there is an even temperature gradient from surface to bed without any definite thermocline. The profile is almost fully mixed in the remainder of the year.

Station KP1

At KP1 on the eastern side of the lake outside Rusinga Channel (Figure 1.5) the pattern is similar to UP2, but the temperature gradients from surface to bed are generally weaker. Full mixing occurs in January and July-August.

Station UP10

At UP10 in the deeper eastern central part of the lake (Figure 1.6) there is significant stratification February to May with a thermocline at around 40 m depth. Like UP6, it is mixed for the remainder of the year. The thermocline at 5 m at end September may be the start of a general stratification, but could also just be a diurnal phenomena.

Station TP12

The pattern at TP12 in the south central lake (Figure 1.7) is similar to UP10 with stratification occurring February to May, although the development of the stratification is delayed compared to the northern part of the lake. Full mixing occurred in January and July-August, with weak temperature gradients in the remainder of the year.

Station TP4

The final example of temperature profile time series is shown in Figure 1.8 for TP4 near the southern end of the lake. This confirms the later development of the stratification, here seen only in May. Weak vertical temperature gradients occur during the rest of the year. The weather conditions here seem to be quieter than further north since full vertical mixing does not occur. Further, there is generally less temperature difference between surface and bed.

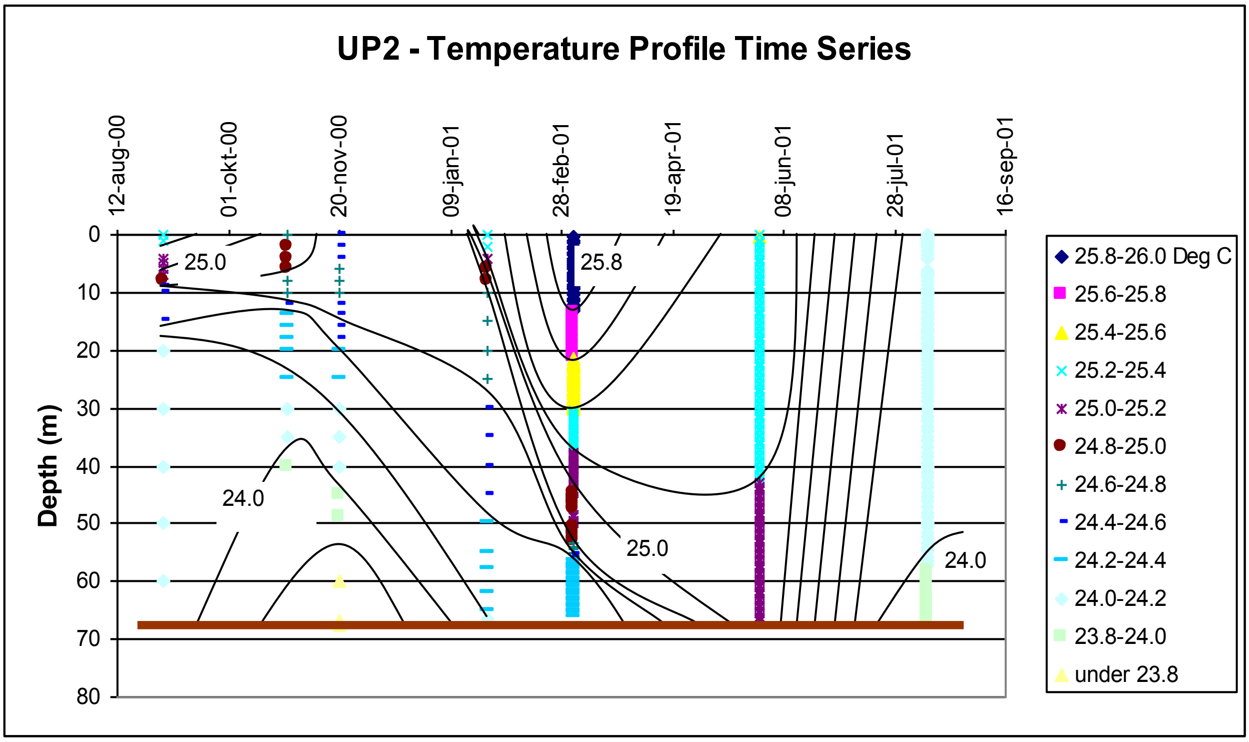

Figure 1.3 Time series of temperature profiles at UP2, 2000-2001.

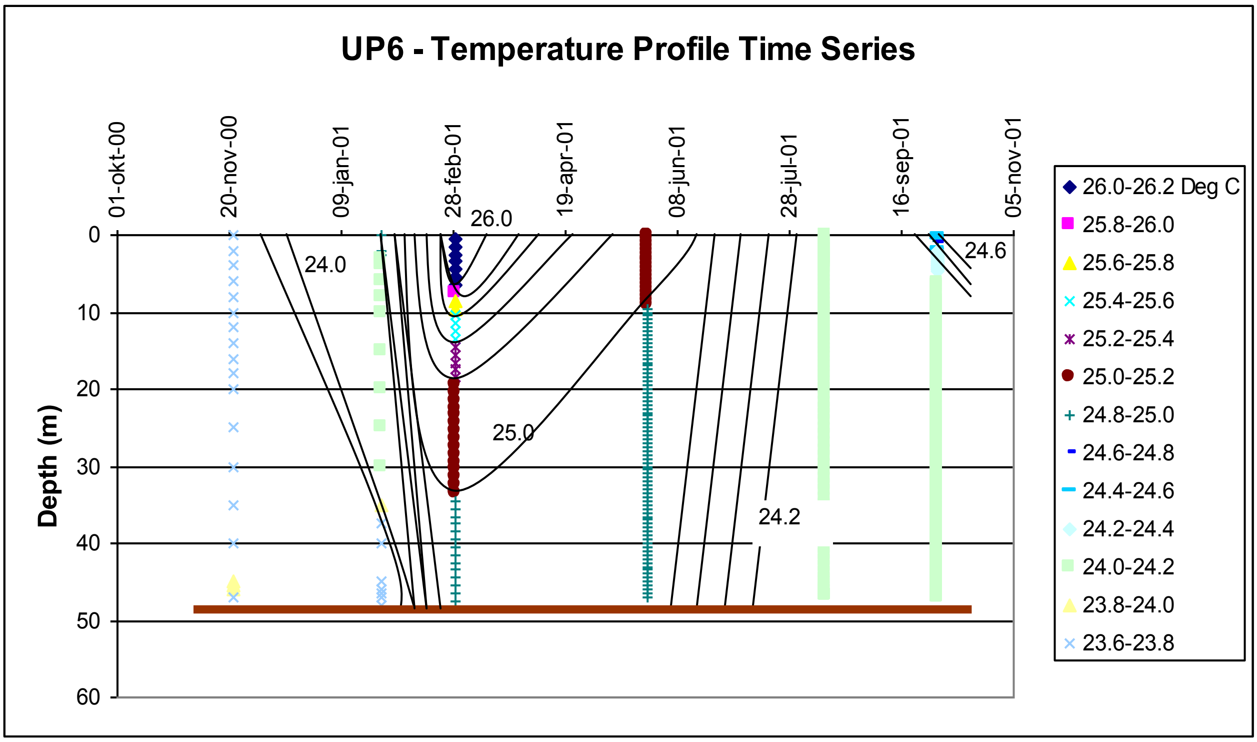

Figure 1.4 Time series of temperature profiles at UP6, 2000-2001.

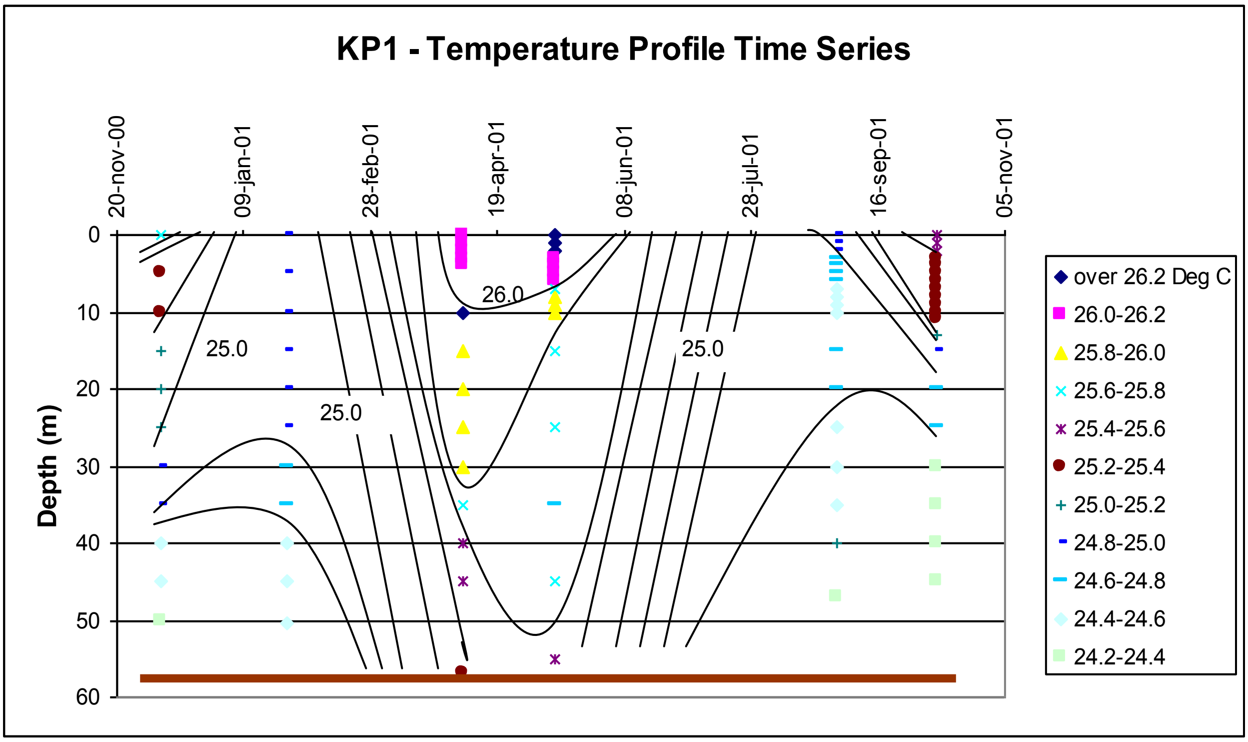

Figure 1.5 Time series of temperature profiles at KP1, 2000-2001.

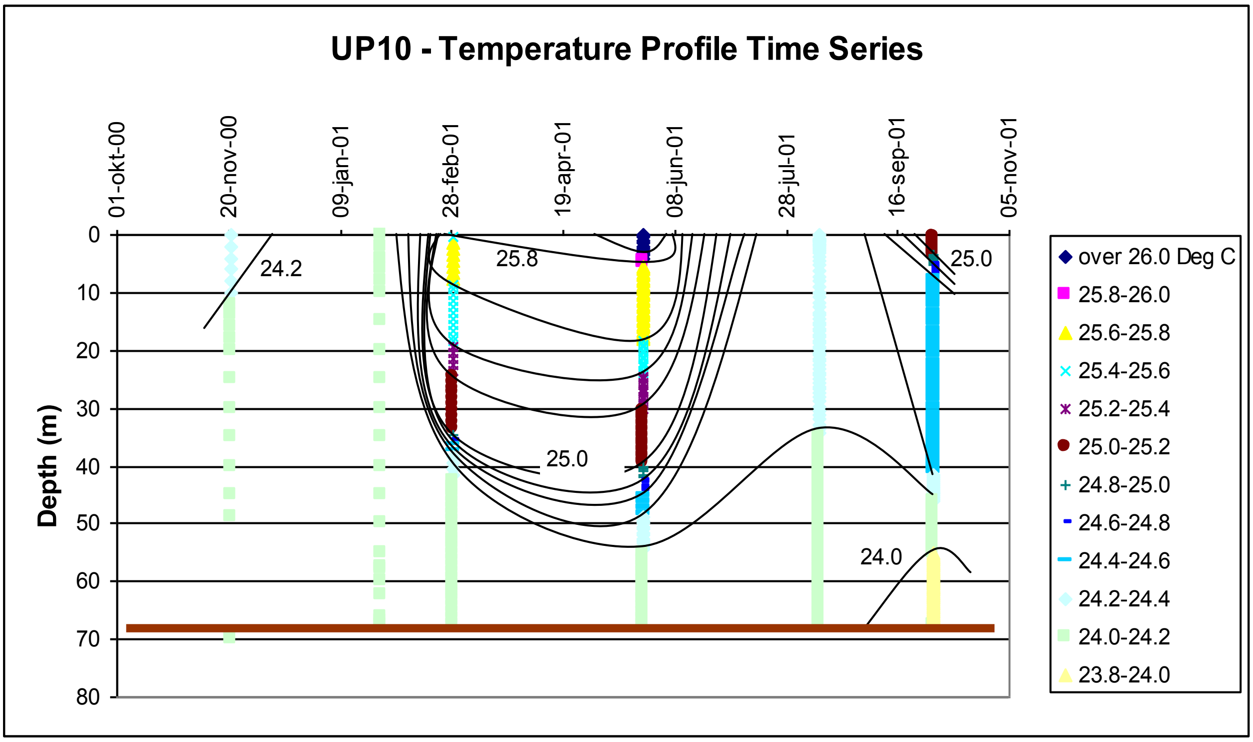

Figure 1.6 Time series of temperature profiles at UP10, 2000-2001.

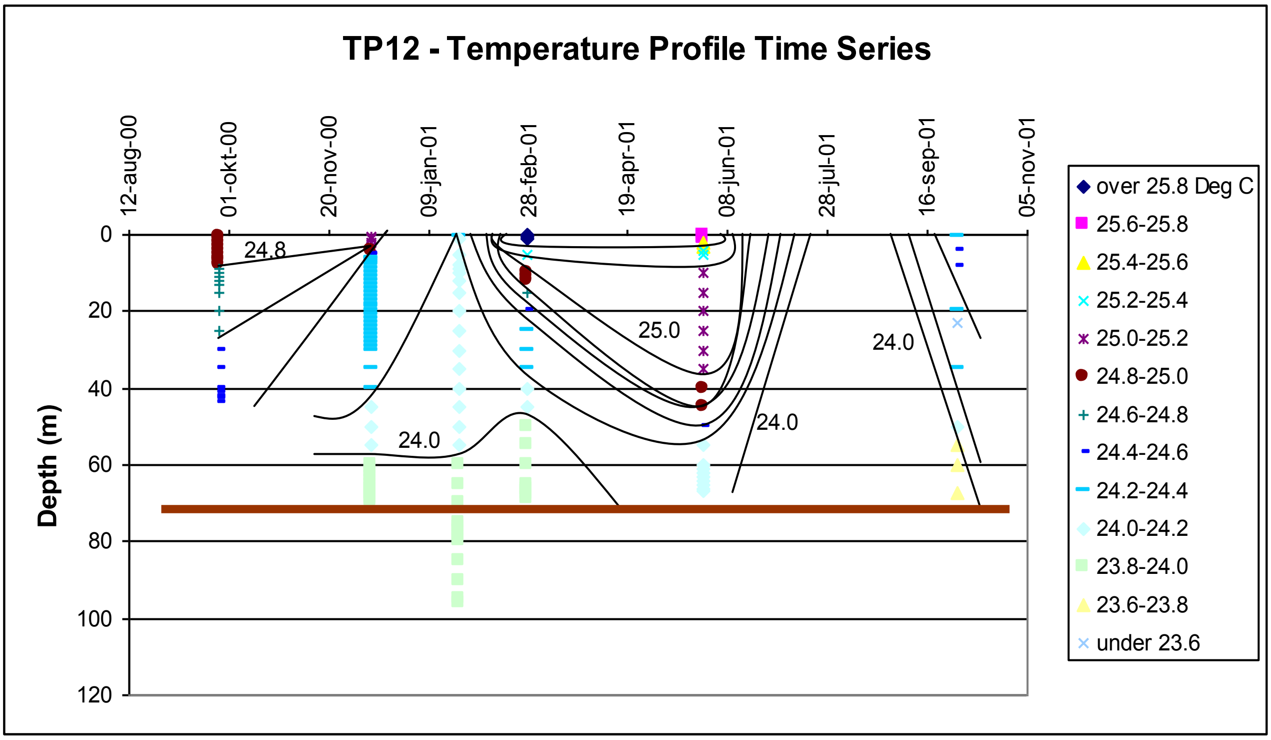

Figure 1.7 Time series of temperature profiles at TP12, 2000-2001.

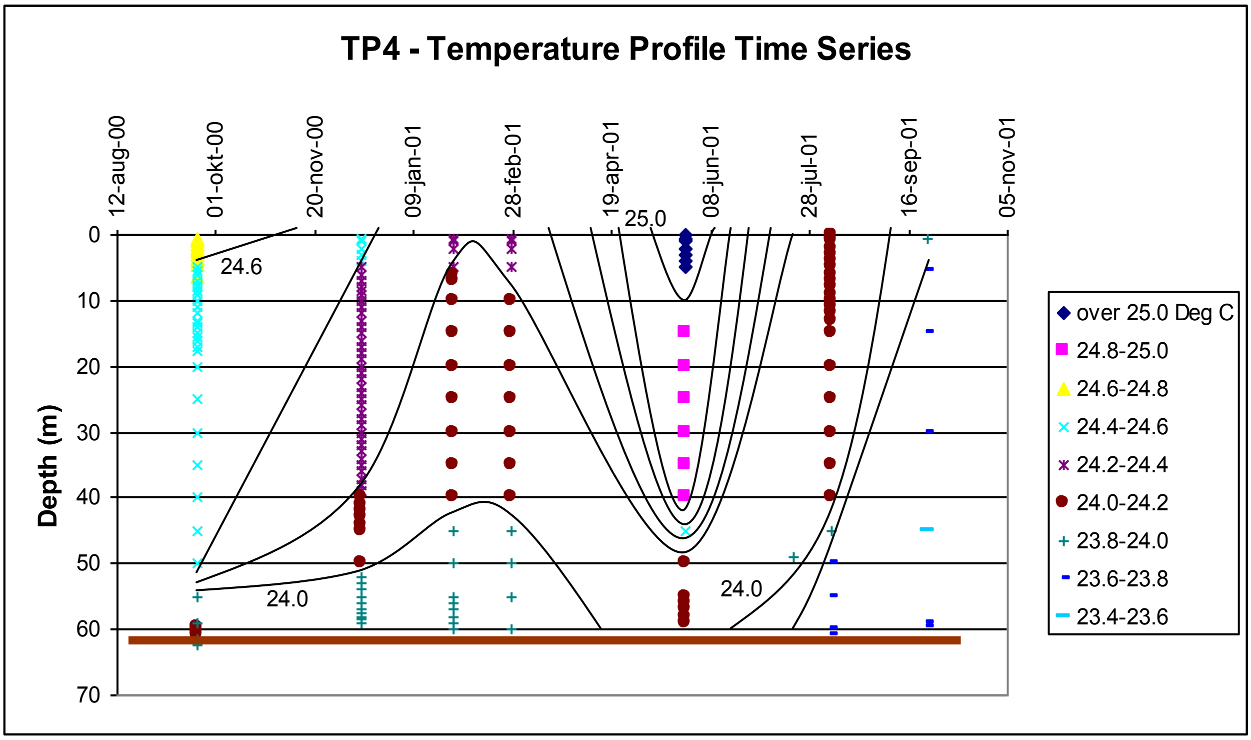

Figure 1.8 Time series of temperature profiles at TP4, 2000-2001.

1.5.2 Transects of Temperature Profiles

It is also interesting to examine the temperature profiles along and across Lake Victoria at a number of instants in time. This can illustrate the variations from north to south and east to west at any one instant.

The locations of the monitoring stations were specifically selected to lie on transects through the lake as shown in F. Some examples of temperature profiles along the transects are shown in F to F. Note that the measurements at the stations along a transect are not simultaneous but are generally take within a period of two weeks unless specifically noted in the descriptions below.

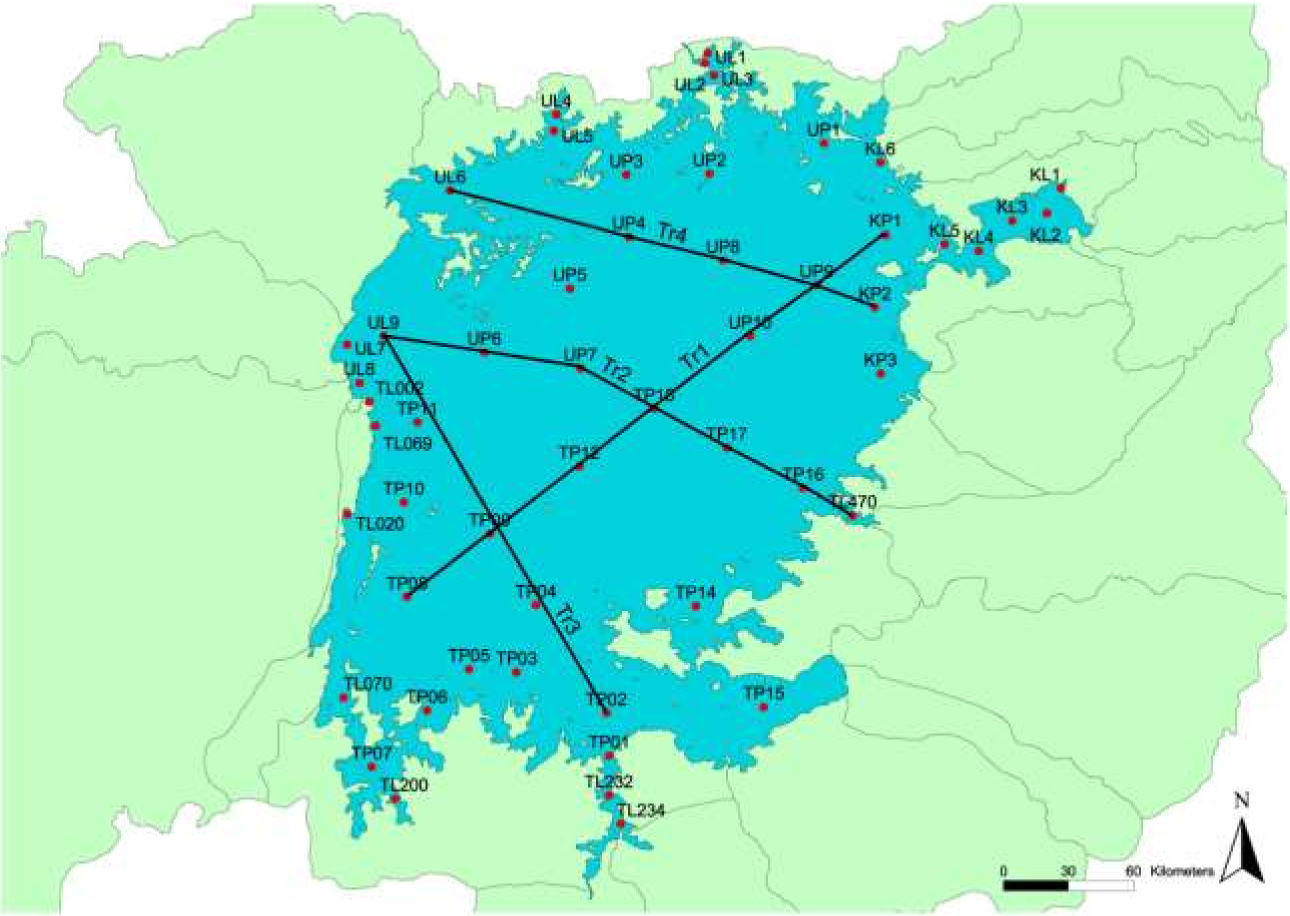

Figure 1.9 Lake monitoring stations and transects.

Transect 1

Transect 1 goes from the southwest corner to the northeast corner of the lake. The temperature profiles in November-December 2000 show an almost well-mixed lake except at KP1 in the northeast. The thermocline at 4 m depth at TP12 is probably a diurnal effect. It also shows somewhat warmer temperatures in the north than in the south, a tendency that is seen throughout the year.

In January 2001 the lake is well-mixed everywhere except, once again, at KP1 in the northeast. In fact, almost all the profiles along the Kenyan and eastern Tanzanian coasts showed stratification throughout the year, indicating that the area is protected from the winds that cause mixing elsewhere.

F clearly shows the deep thermocline (50 m) which develops in May. However, the conditions above the thermocline vary greatly from south to north, with a well-mixed epilimnion in the south and larger vertical temperature gradients in the north.

Transect 2
A single set of profiles along transect 2 in August 2001 is shown in F. This shows, as expected, a well-mixed lake on the Ugandan side with a slight stratification on the eastern, Tanzanian side.

Transect 3
F shows transect 3 in July-August 2001. Again, the lake is well-mixed in this period, with a tendency for slight stratification in the south east corner. It also confirms the tendency for cooler temperatures at the southern end of the lake as seen along transect 1.

Transect 4
The profiles along transect 4 across the northern end of the lake are shown in F for March 2001 and in F for October 2001. The results in March confirm the formation of the deep thermocline as seen in May along transect 1. They also confirn the observation that the conditions above the thermocline vary greatly across the lake. (Note that the profile at KP2 is from 22 January, some 5 weeks before the other profiles.)

The gradual redevelopment of stratification in October after the full mixing in July-August is seen in F. The stratification starts at the surface and the heat is slowly transported downwards so that by October it has reached depths of 30-40 m. The deeper waters are still homogeneous. Once again, it is seen that the western side of the lake is more mixed than the eastern side which is more protected from the wind.

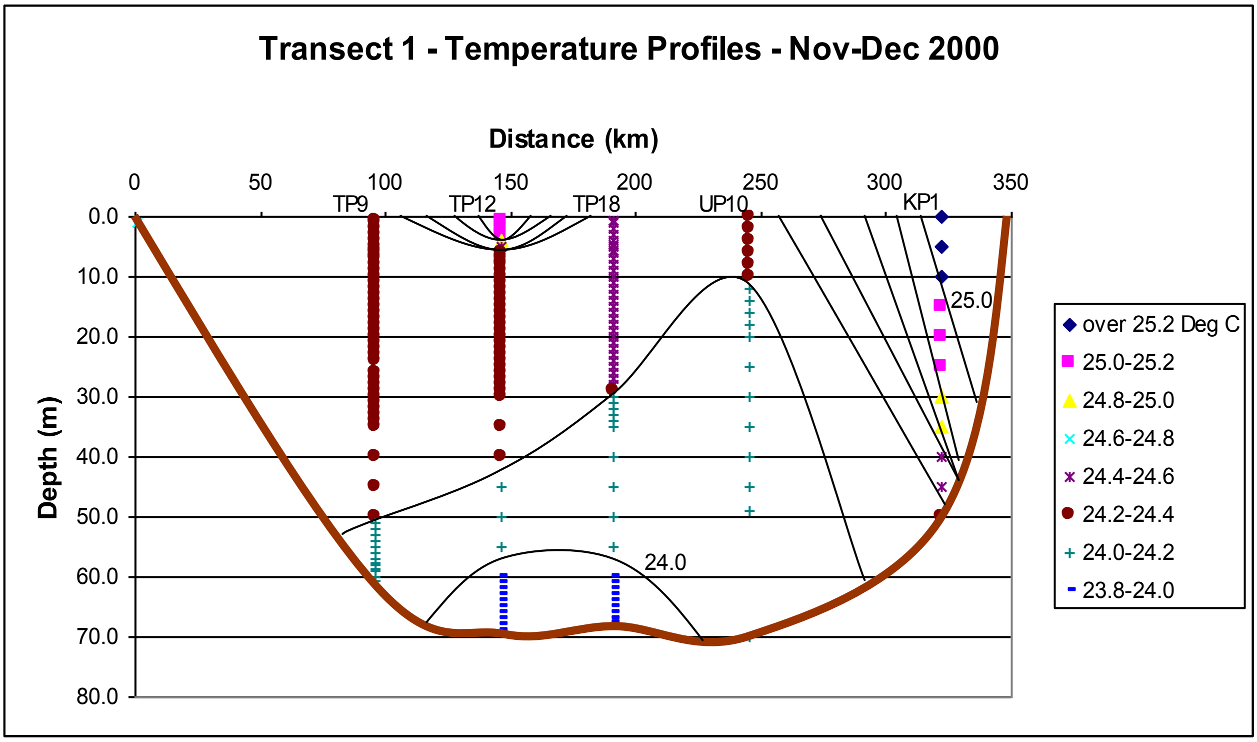

Figure 1.10 Temperature profiles along transect 1, November-December 2000.

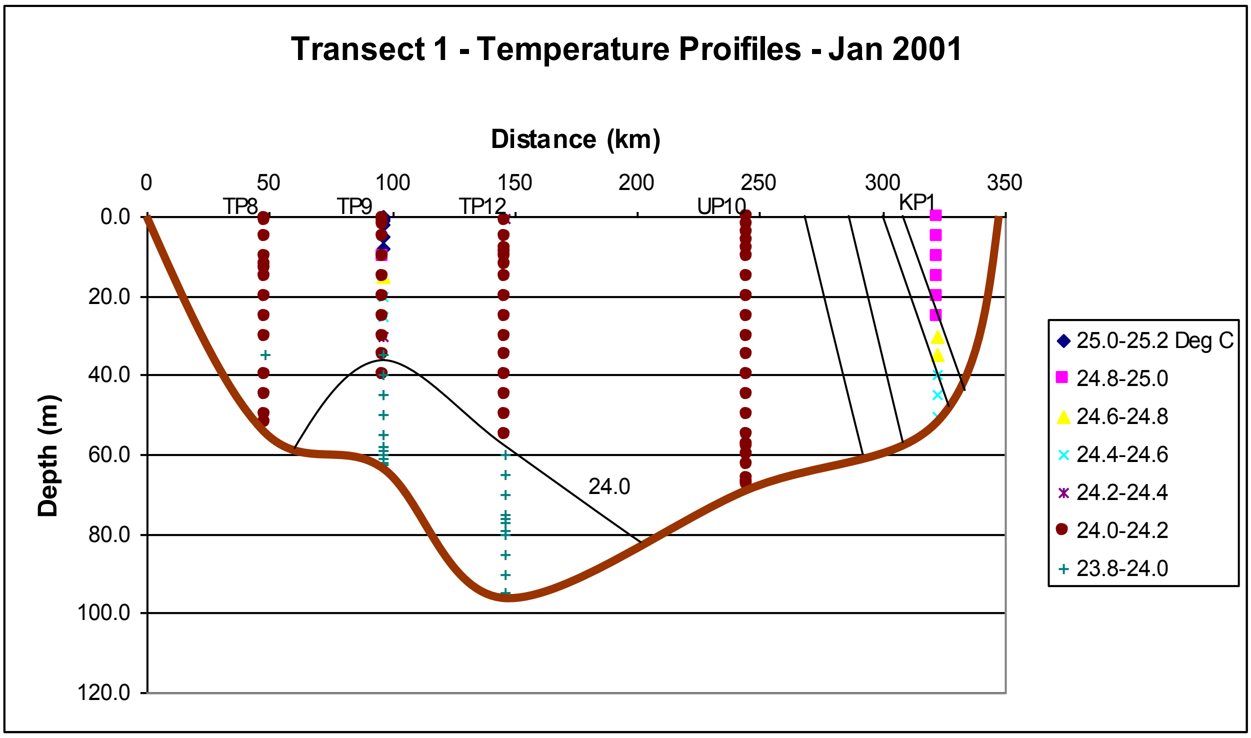

Figure 1.11 Temperature profiles along transect 1, January 2001.

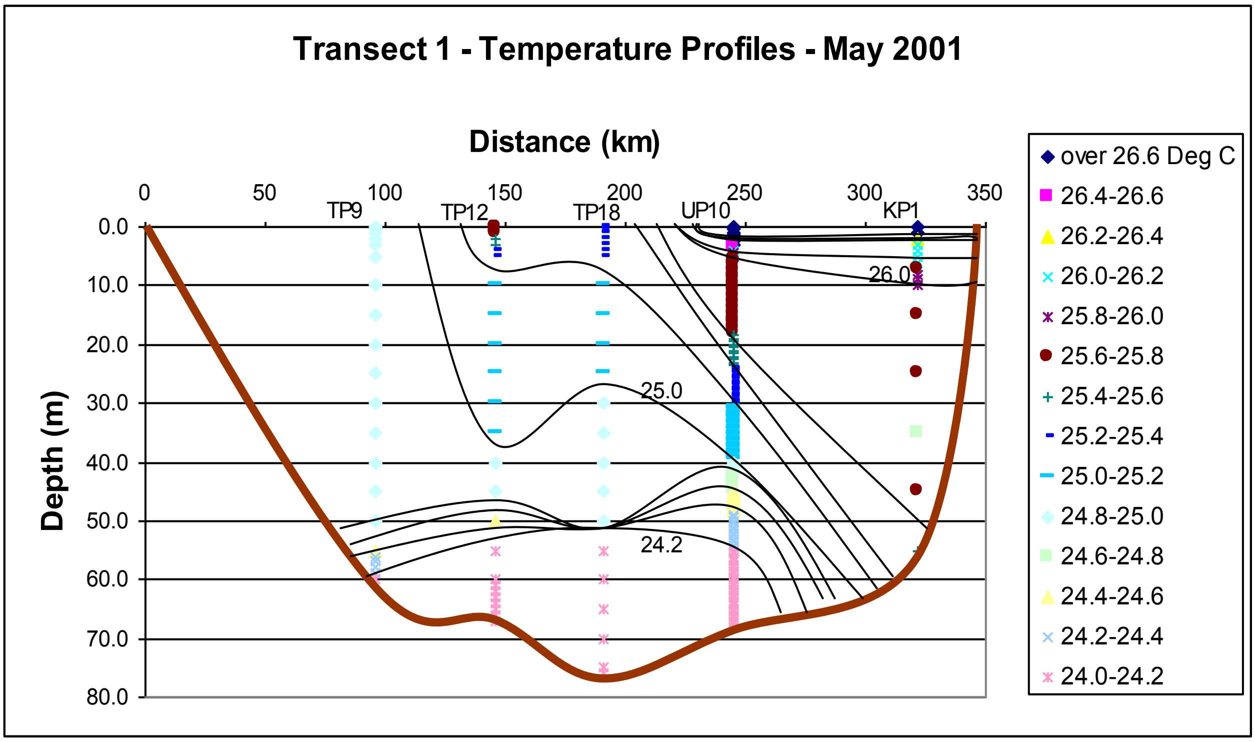

Figure 1.12 Temperature profiles along transect 1, May 2001.

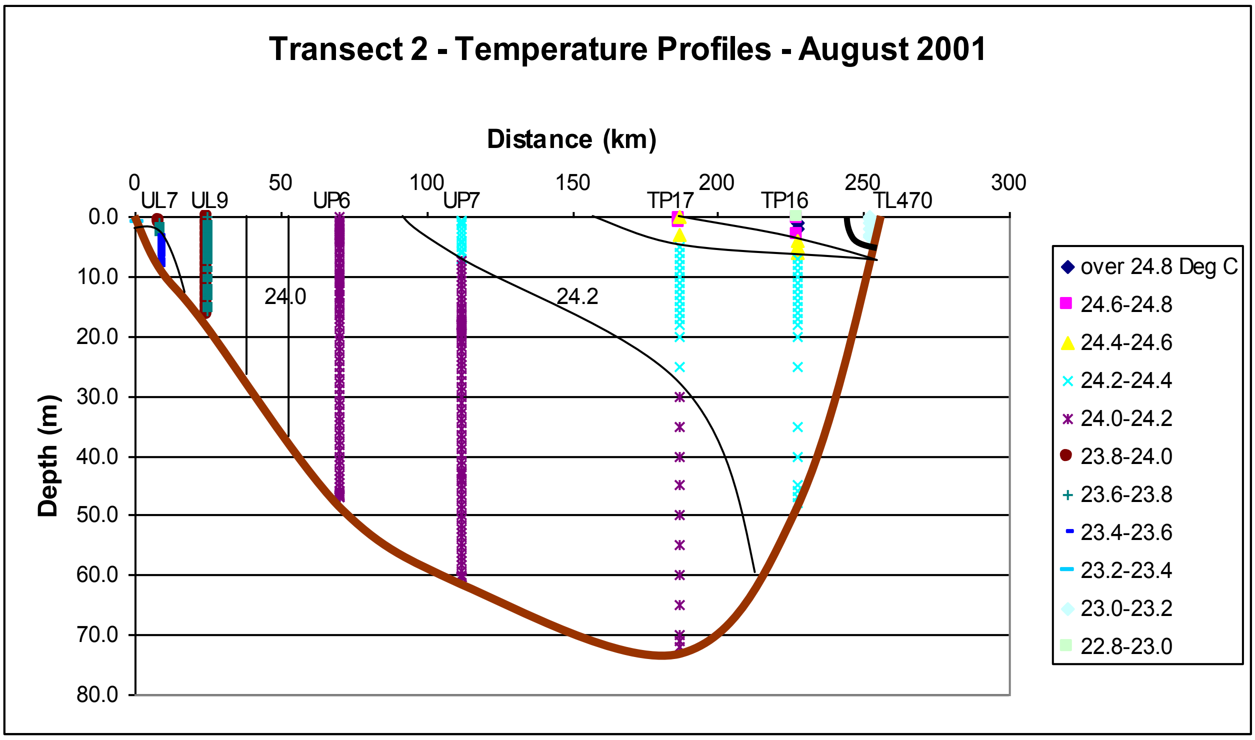

Figure 1.13 Temperature profiles along transect 2, August 2001.

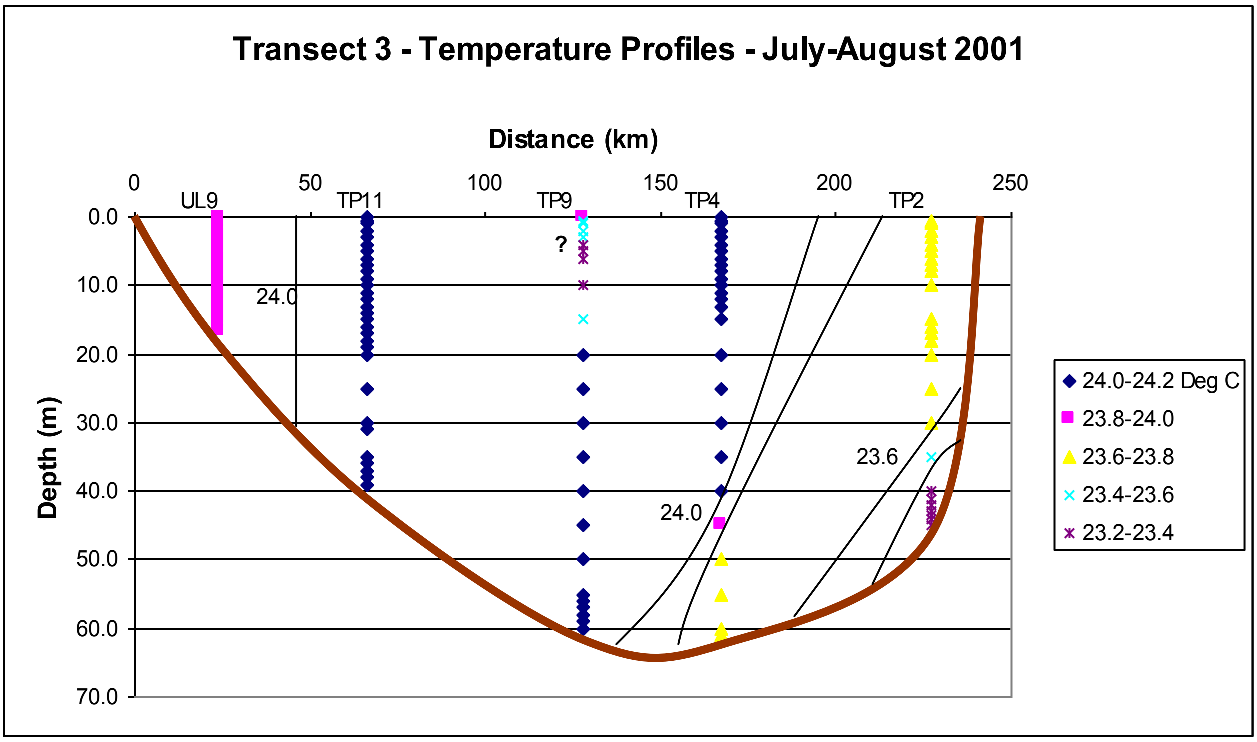

Figure 1.14 Temperature profiles along transect 3, July-August 2001.

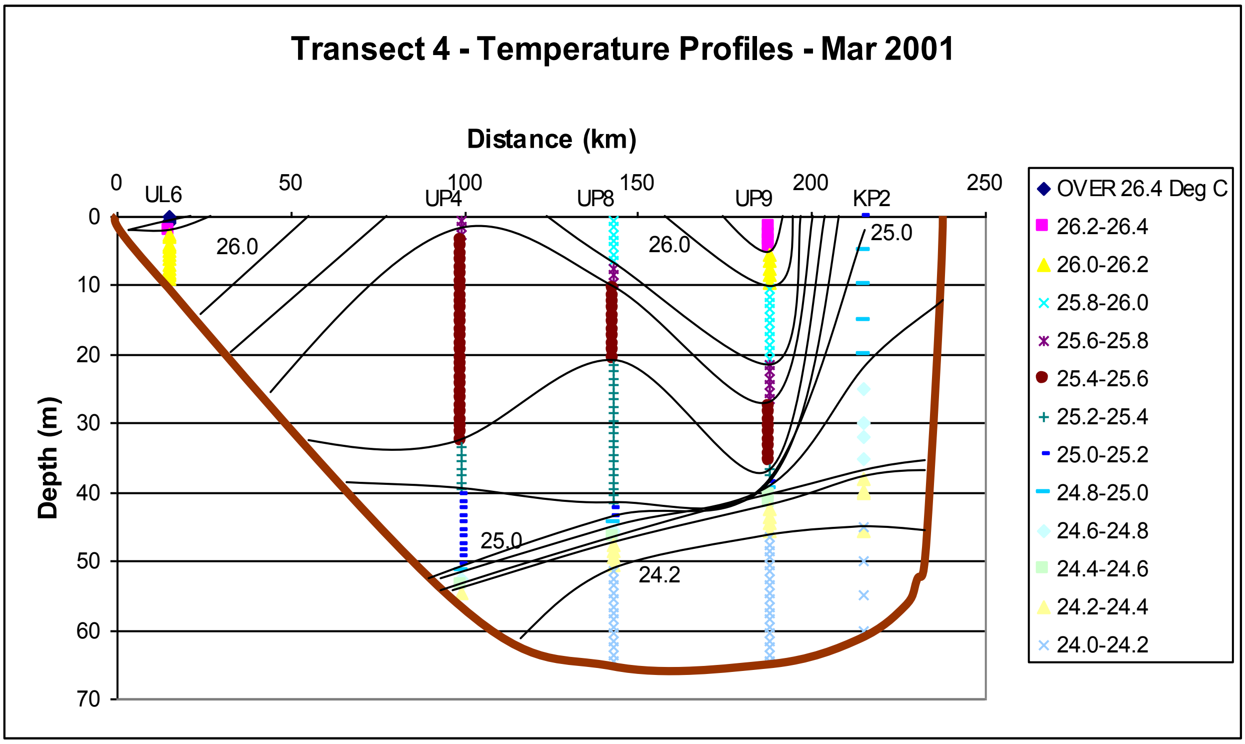

Figure 1.15 Temperature profiles along transect 4, March 2001.

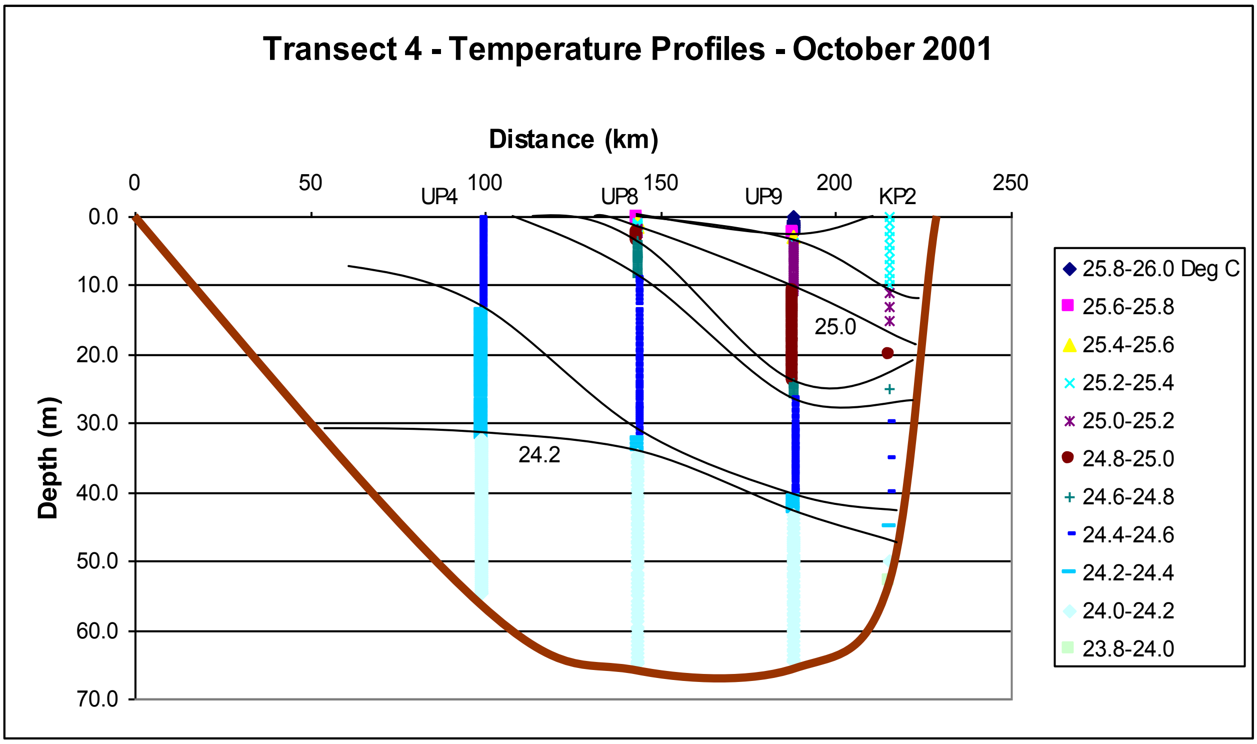

Figure 1.16 Temperature profiles along transect 4, October 2001.

1.5.3 Conclusions

Examination of the temperature profiles leads to the following conclusions:

1. Phase 2 and phase 3 of the annual cycle as defined by Talling have been confirmed. Phase 2 is the development of the deep (50 m) thermocline in the period February to May, and phase 3 is the total vertical mixing that occurs in July-August. Phase 1 (September-December) is less obvious, ie. the gradual warming of the water column is weak, and almost total mixing occurs in December-January at some stations.

2. Lake Victoria is spatially inhomogeneous. At any instant there are large differences in the temperatures and stratification from north to south and east to west. The profile at UP2 (Bugaia Is) cannot be used as an indicator of the conditions everywhere in the lake as has been assumed by various researchers. This is easily understood if the cross-section of the lake is drawn to an undistorted scale. At a scale of 1:1 million, transect 1 would be 350 mm long and 0.07 mm deep, ie. much thinner than a pencil line thickness. Clearly, any hydraulic process can occur in one area of the lake, eg. mixing due to a local thunder storm, without affecting the rest of the lake

3. In general, there is less vertical mixing on the eastern side of the lake, including the southeastern corner. A possible explanation is that the global

winds that cause the mixing come from east and southeast, and the adjacent lake areas are more protected than the western side.

4. The stratification of the water column is more pronounced in the north and central areas than in the south.

5. There is a tendency for the entire water column to be slightly warmer in the north than in the south.

1.6 Thermal Stratification in Winam Gulf

Temperature profiles were measured at KL1 to KL 5 in Winam Gulf in December 2000 and January, April, May, August and October 2001. These showed that the water temperatures in Winam Gulf are about 2 Deg C higher than in offshore Lake Victoria.

The temperatures seem to vary in an irregular manner from Kisumu out to Rusinga Channel. Such a case is illustrated in Figure 1.17 in December 2000. This could perhaps be explained by the discharges from the rivers and streams into the Gulf. The Nyando and Sondu Rivers have significant flows all year round, and there are many additional small discharges from the streams in the North and South Awach. The temperatures of the discharges will be different from each other and different from the lake, and could cause the irregular variations of the water temperatures that are observed. This hypothesis should be investigated further in the next phase of LVEMP.

There is also frequently a strong thermocline close to the surface as shown in Figure 1.18. The thermocline could be the result of solar heating during daylight, and this could be verified by making some measurements at night or very early in the morning. Figure 1.18 also shows a tongue of cooler water starting near KL2 and flowing along the bed out into the lake. The cooler water could originate from the Nyando River.

It is difficult to come to any conclusion about the importance of the thermal stratification as a flushing mechanism for Winam Gulf. On the other hand, the discharges from the rivers will definitely give a net outflow, and thereby a flushing of the gulf. Also, it is known that there are strong currents in Rusinga Channel both into and out of the gulf, probably correlated to the diurnal onshore-offshore wind pattern. These wind driven currents will also contribute to the flushing.

The field monitoring should continue in the next phase of LVEMP, and be extended with current profiling particularly in Rusinga Channel, and with regular measurements of the water temperature in the rivers. The field monitoring itself is not sufficient, and should be supplemented with detailed modelling of the gulf to quantify the various hydraulic processes.

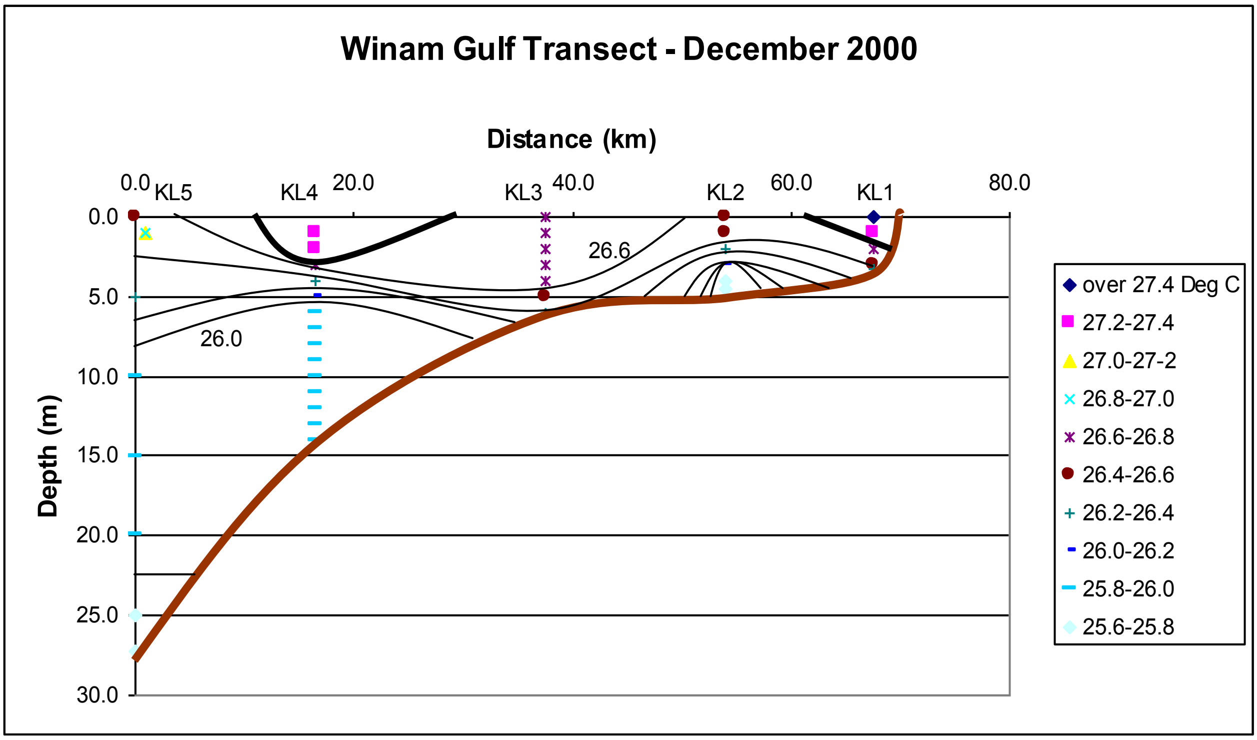

Figure 1.17 Temperature profiles on a transect of Winam Gulf, December 2000.

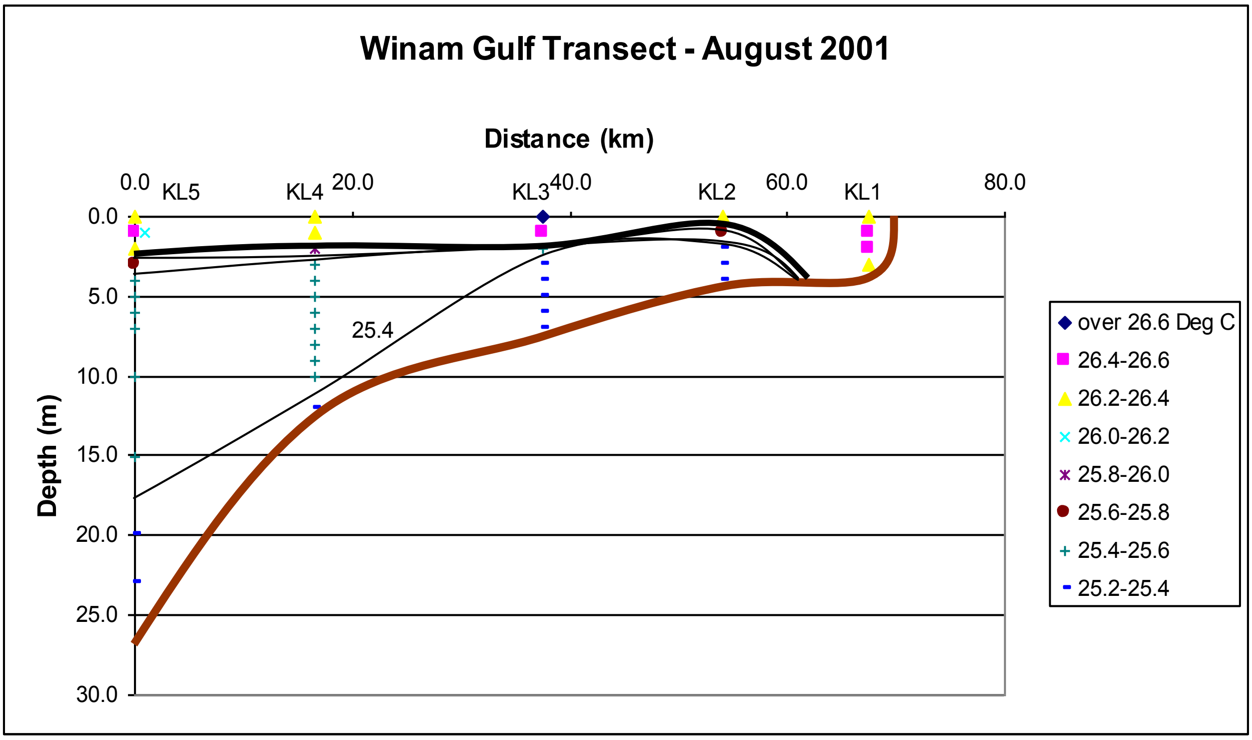

Figure 1.18 Temperature profiles on a transect of Winam Gulf, August 2001.

1.7 Thermal Stratification in Mwanza Gulf

Temperature profiles were measured at stations TL234, TL232, TP1 and TP2 in Mwanza Gulf in December 2000 and January, February, May and July 2001. These showed that Mwanza Gulf has quite different thermal stratification characteristics from the adjacent waters of Lake Victoria as represented by TP2. In most cases there are significant spatial temperature differences between the uppermost parts of the gulf (TL234) and the mouth of the gulf at TP1.

Another point worth noting is that the temperatures in the uppermost parts of the gulf (TL234) are mostly cooler than the lake. Only in February were they warmer. The cooler water will contribute to the flushing of the gulf by vertical circulation, and should be investigated more closely in the next phase of LVEMP.

Two examples of the temperature profiles along the gulf are shown in Figure 1.19 and Figure 1.20. In January, the cooler water has formed a tongue which flows out into the lake along the bed and finally mixes with the lake water between TP1 and TP2. There is also a significant stratification at the surface in the upper gulf.

May is the period of most stratification in the lake, but the thermocline lies at around 50 m depth and does not affect Mwanza Gulf. However, May shows once again the cooler water in the upper gulf and the surface stratification that this time extends out to TP2.

In conclusion, thermal stratification seems to exist most of the time in Mwanza Gulf. It is likely to cause a vertical circulation with the cooler water flowing out at the bed and warmer water flowing in from the lake at the surface. In turn, the vertical circulation could give a significant flushing of the gulf. These phenomena should be investigated further in the next phase of LVEMP, along with the source of the cooler water. Current profile measurements should be made to test the hypothesis of vertical circulation.

Periodic inflows from rivers will also contribute to the flushing of Mwanza Gulf.

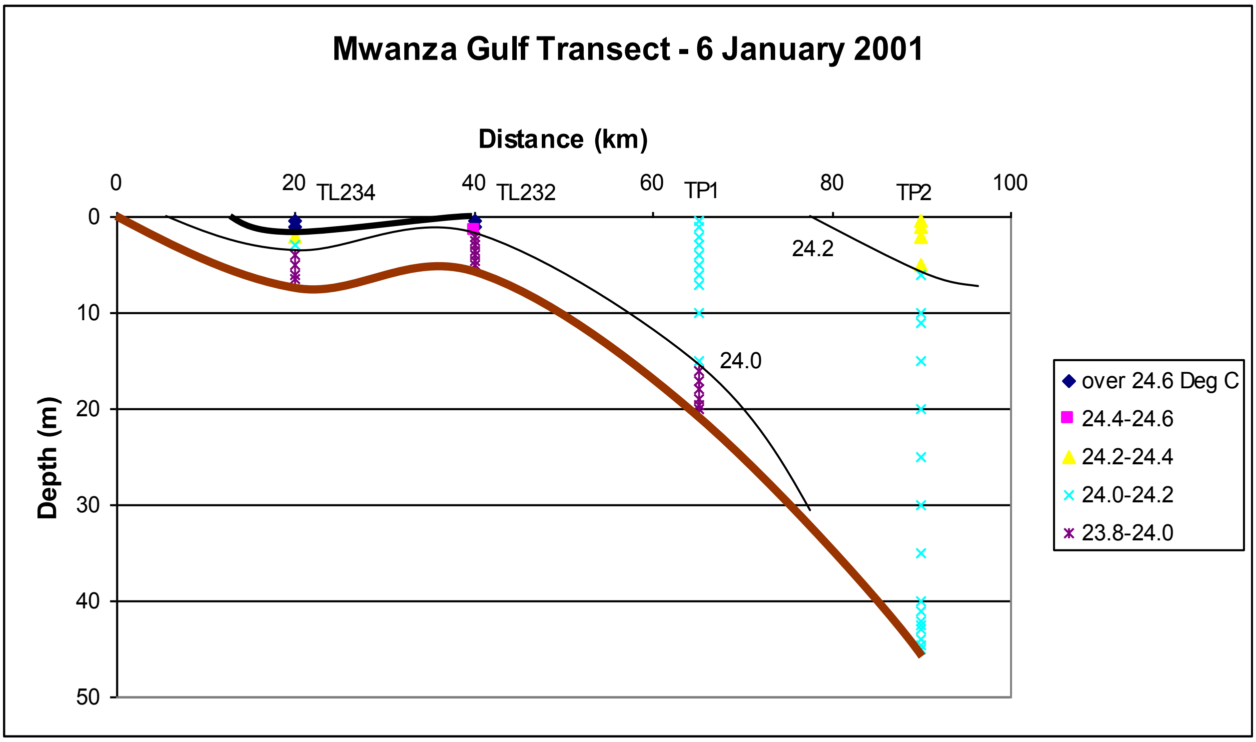

Figure 1.19 Temperature profiles on a transect of Mwanza Gulf, 6 January 2001.

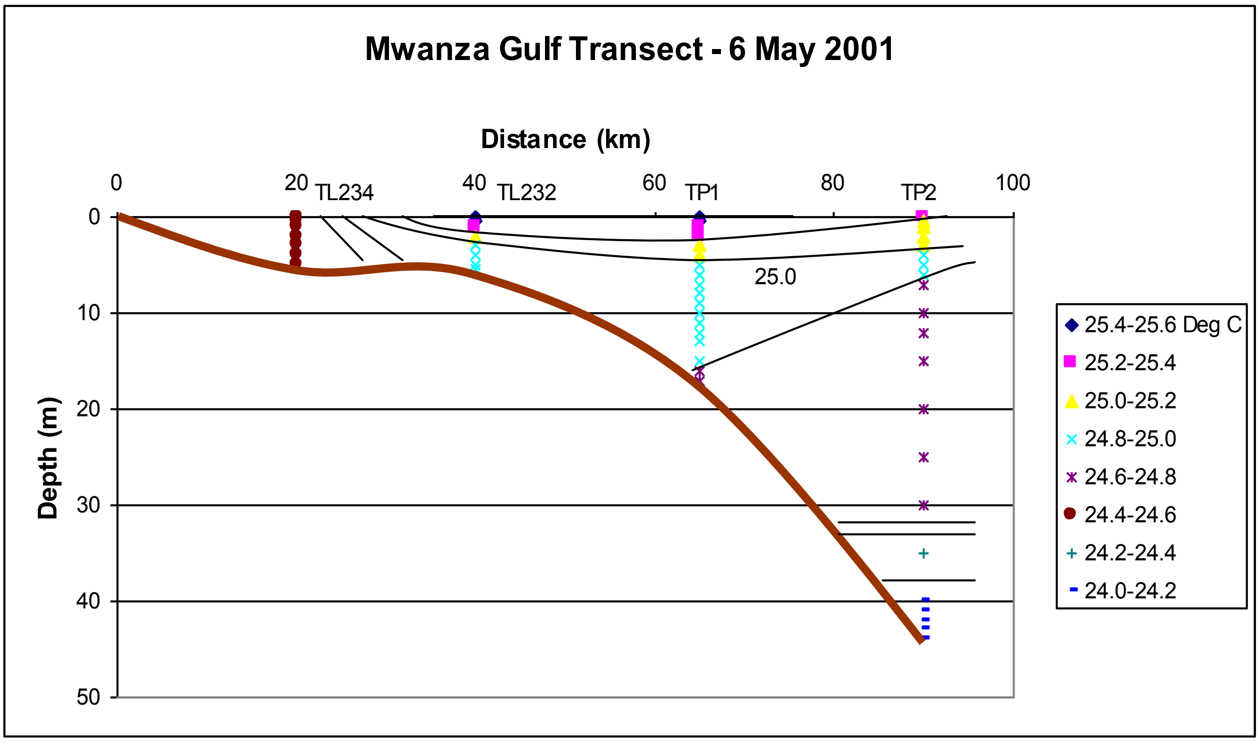

Figure 1.20 Temperature profiles on a transect of Mwanza Gulf, 6 May 2001.

1.8 Thermal Stratification in Napoleon Bay

Temperature profiles were measured at stations UL1, Ul2 and UL3 in Napoleon Gulf in December 2000 and January, February, May, July, August and September 2001. As with Winam Gulf, the water temperatures in Napoleon Gulf are about 2 Deg C warmer than offshore Lake Victoria.

There seem to be two typical conditions in the gulf. For about 50% of the time the vertical temperature profiles throughout the gulf are similar without any strong thermocline and only small temperature differences between surface and bed. Such a situation is shown in Figure 1.21 for August 2001.

The second condition is characterised by similar profiles at UL2 and UL3, but at UL1 the temperature is warmer by 1 Deg C or more. See Figure 1.22 for September 2001. This could be explained by the fact that UL1 is in the quiet and shallow bay near Jinja harbour and can be heated more by the sun. UL2 and UL3 are more influenced by the lake, particularly because they are in the main outflow channel to the Victoria Nile.

The hydraulic conditions in Napoleon Gulf are constant and there is unlikely to be any significant horizontal or vertical circulations, apart from the Victoria Nile outflow. The gulf is not interesting as a focus area for further study.

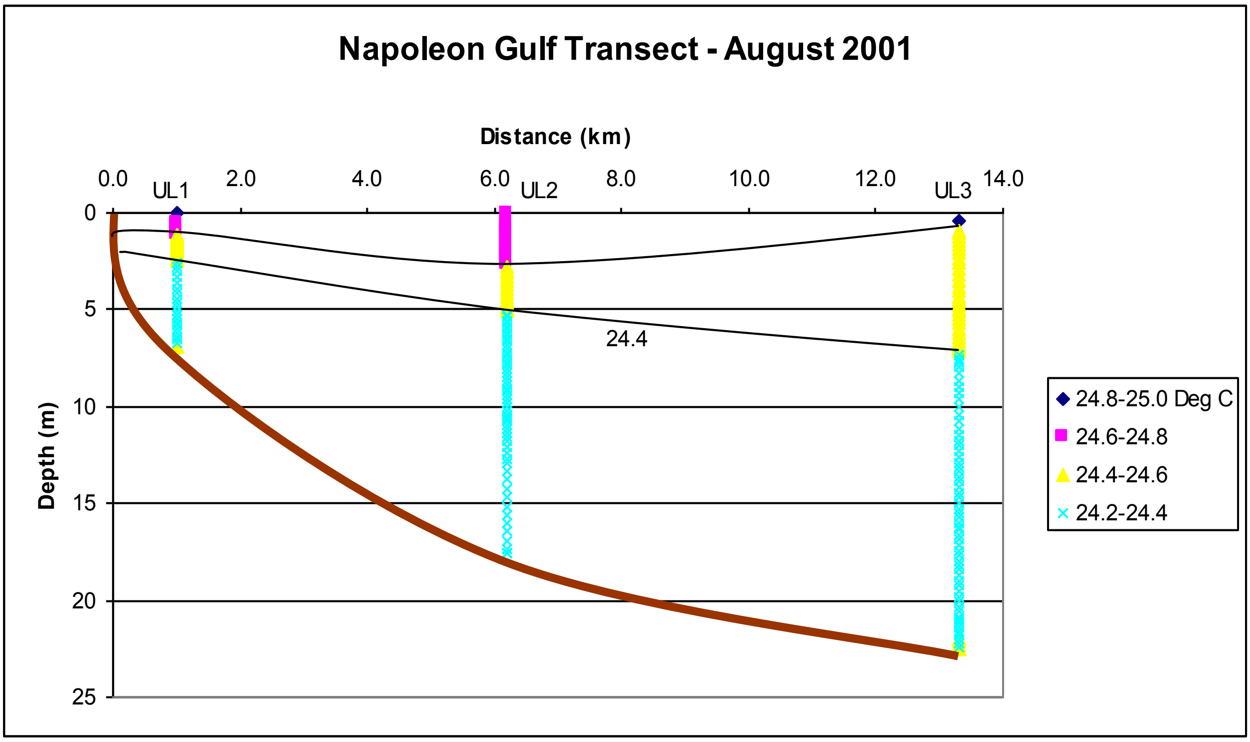

Figure 1.21 Temperature profiles on a transect of Napoleon Gulf, August 2001.

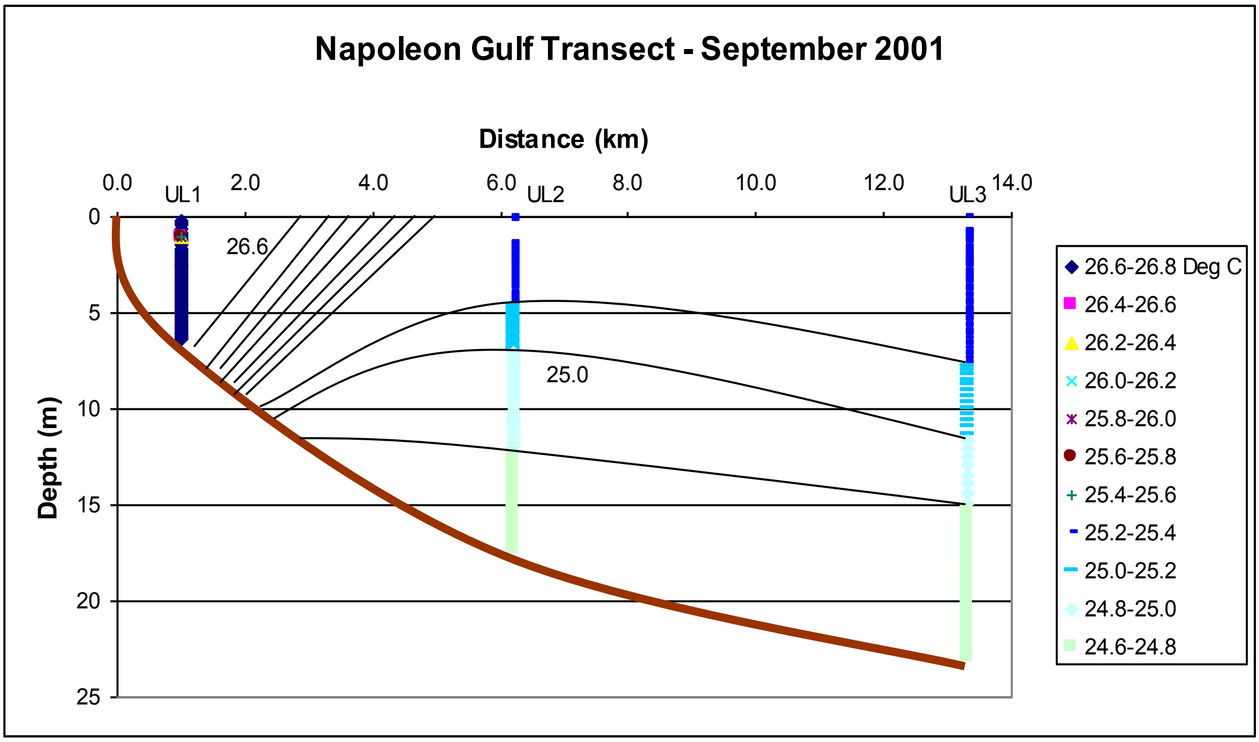

Figure 1.22 Temperature profiles on a transect of Napoleon Gulf, September 2001.

1.9 Currents

Vertical current profiles were measured with an ADCP by the Ugandan team during all their lake cruises after November 2000. There are 8 sets of data in all.

The survey vessel was anchored at each station and, after becoming stationary, the wind speed and direction was measured with a manual anemometer and then the vertical current profile.

The average current was calculated for a number of layers to ease the comparison between stations. The layers were:

0 - 5 meters depth (surface)
5 - 10 m
10 - 20 m
20 - 30 m
30 - 40 m
below 40 m depth

The profiles were examined and showed weak velocities (less than 0.1 m/s) with highly irregular directions between adjacent layers, and even from meter to meter over the depth. Only few recordings showed any resemblance of consistency.

Spatial plots were made of the wind vectors and current vectors in each of the layers for each of the cruises. Some examples are shown below. It should be noted that the stations were not measured simultaneously, but over a period of 2-3 days. However, if there were any large scale circulation patterns in the lake, one would expect to see them in the spatial plots.

The analysis showed that there is rarely any recognisable large scale circulation pattern in the Ugandan waters. As already noted, the currents are weak (less than 0.1 m/s) and frequently in opposite directions at adjacent stations. Similarly, the winds rarely show any consistency in speed and direction from station to station. Further, there is little correlation between the wind and the surface current speeds and directions. An example is shown in Figure 1.23 to Figure 1.26 for February 2001.

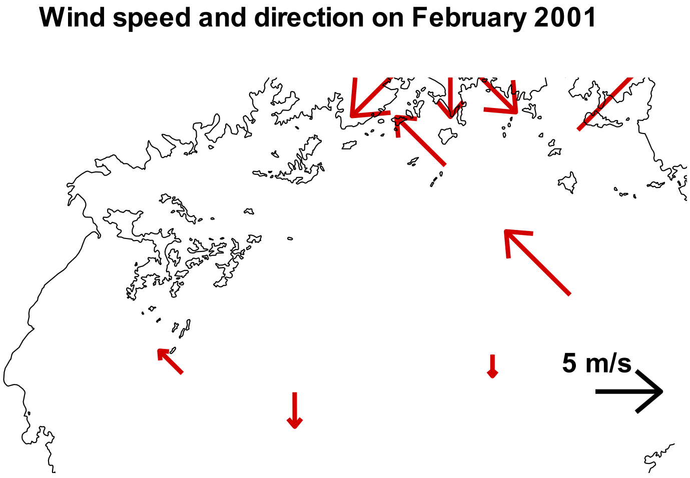

Figure 1.23 Wind speeds and directions at Ugandan lake monitoring stations in February 2001.

Average velocities at the water surface

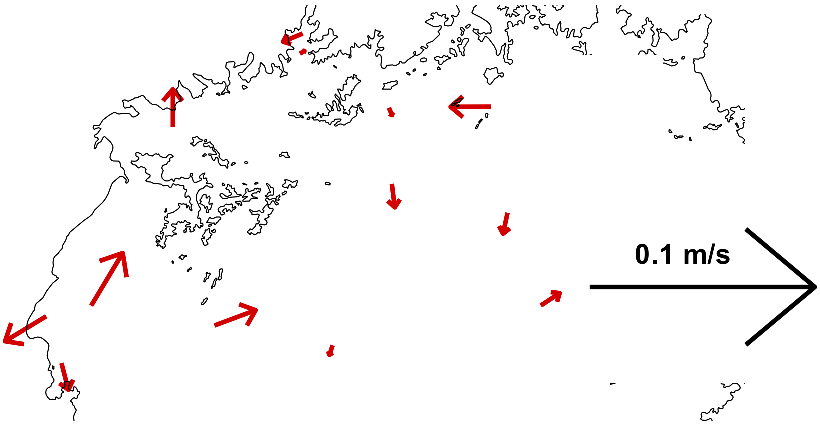

Figure 1.24 Surface current speeds and directions at Ugandan lake monitoring stations in February 2001.

Average velocities for depths between 5 and 10 meters

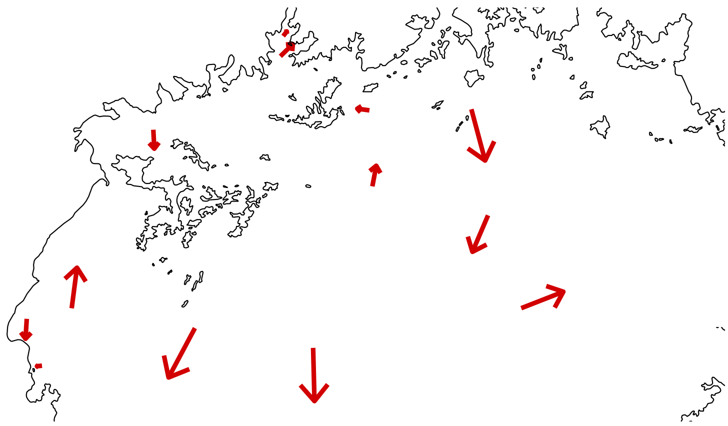

Figure 1.25 Current speeds and directions 5-10 m at Ugandan lake monitoring stations in February 2001.

Average velocities for depths between 30 and 40 meters

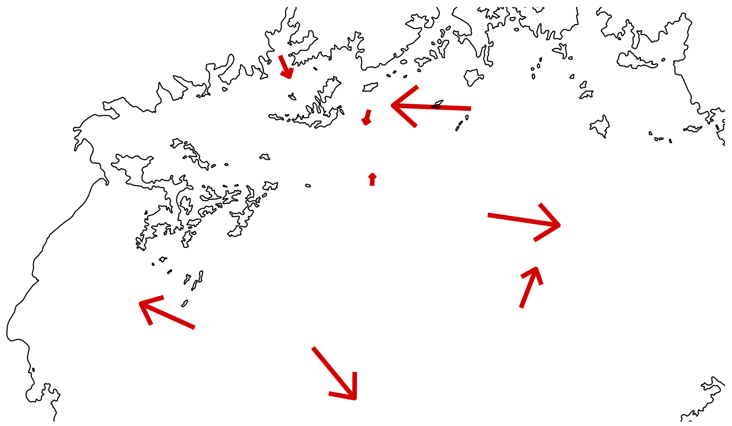

Figure 1.26 Current speeds and directions 30-40 m at Ugandan lake monitoring stations in February 2001.

Based on the available data, the preliminary conclusion is that, for most of the year, there does not seem to be any recognisable, large-scale horizontal circulation pattern in Lake Victoria.

However, it is possible that strong winds in July - Aug (the cause of the total vertical mixing) could cause large scale circulations. This hypothesis should be tested by measurements in the lake.

The consequence of the lack of large scale circulations is that the spreading of pollutants from the nearshore areas to the centre of the lake during most of the year is mainly caused by dispersion and not by advection.

It is strongly recommended that the field measurement campaign with ADCPs should be continued for several years to confirm or reject the preliminary conclusion. The measurements should be made over the whole lake within a short period each month, say maximum 1 week. The campaign should include both measurements from the survey vessels during the monthly lake cruises and continuous measurements a 1-2 stations in each country by bottom deployed ADCPs.