

Chapter 2 (Annex)

Transport of Linthipe River Suspended Sediments in Lake Malawi/Nyasa

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Introduction

The primary objective of the Lake Malawi sedimentation study is to determine and model the spatial and temporal dynamics of sediment delivery into Lake Malawi from the Linthipe River, with particular emphasis on the effects of potential changes in fluvial sediment load and concentration, and the relationship with nearshore lake circulation. In addition to a detailed study of the Linthipe River plume, surface suspended sediment patterns at the mouths of all major rivers influent to Lake Malawi will be mapped seasonally over two years. This report encompasses only a preliminary assessment of water column profile measurements of temperature, conductivity and suspended sediment concentration near the mouth of the Linthipe River during the 1998 rainy season.

Suspended sediment discharged into Lake Malawi via the rivers of its catchment limits light necessary for photosynthesis even as it delivers nutrients to the water column and lake bottom. The impact of increased sediment loading on either primary production or littoral habitat depends very much on the concentrations in which it is delivered, on the depth through which the sediment-bearing fluvial plume spreads, and on the area over which it is transported and deposited. For the Linthipe River, at least part of the sediment load mixes in the near surface waters of Lake Malawi and is borne up to 10s of kilometres, as is evidenced by the visible surface plume that typically spreads out to the north east. However, river water densities associated with many flow events are great enough relative to the lake vertical density structure that a significant part of the river flow plunges and follows the bottom until it attains buoyancy and is borne laterally, forming thin turbid layers spreading out into the lake. This process is described below.

Methods

Water column observations of Lake Malawi temperature, conductivity and optical backscatter were made using a Brancker XL400 CTD logger (CTD/O), and of temperature, conductivity and transmission over a 0.25 m path using a Seabird CTD logger (CTD/T). The sensors on the CTD/O logger were checked and calibrated by Richard Brancker Research in November, 1997. Water temperature and conductivity probes on the two CTDs were cross-calibrated, and CTD/T data were adjusted slightly to fit CTD/O data. All conductivities reported are adjusted to a water temperature of 20°C, using the equations of Wüest et al (1996). Optical data recorded by the CTD/O and CTD/T loggers were empirically calibrated for suspended sediment concentration (TSS) by regression on sediment concentration determined by filtration (1 µm GF/C filters). The CTD/O optical backscatter

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meter discriminates Lake Malawi TSS well over a range of 1-3500 mg·L⁻¹ ($r^2=0.99$, $n=57$, based on preliminary weighing of filtered samples) but is a less precise estimator of TSS below 10 mg·L⁻¹. The CTD/T beam transmissometer discriminates TSS in the range 0.1-40 mg·L⁻¹ ($r^2=0.82$, $n=34$, based on preliminary weighing of filtered samples).

Linthipe River daily discharges are reported by the Water Department, Malawi, at Salima, about 15 km upstream of Lake Malawi. River temperature was recorded continuously (except for short breaks due to the failure of one logger and the loss of another) using Onset Corporation Hobo temperature loggers (precision ~0.1°C) tethered at approximately 0.5 m depth in fast moving water near the bank, approximately 150 m upstream of the river mouth. Three loggers were used over the rainy season sampling period. The three were compared over the river temperature range against a laboratory thermometer, and inter-calibrated prior to deployment. For 8 CTD/O temperature measurements at the standard station, midstream, 300 m upstream of the lake, the CTD/O temperature averaged 0.2 °C less than the Onset logger temperature (standard deviation of the difference: 0.6 °C). River water conductivity was measured using the CTD/O conductivity probe. TSS data reported are a combination of direct filtration data and values calculated from CTD/O optical backscatter observations. Samples for filtration and CTD/O observations reported are vertically integrated over the river depth (typically 0.4-0.8 m) at the midstream station.

River and lake water salinity (for density determination) were calculated from temperature and conductivity data using equations determined by Wüest et al (1996) for Lake Malawi. Specifically, I used equation 5b (p.187) in Wüest et al, for determining the temperature correction (f_T) factor appropriate to a composite curve for Lake Malawi. Because all calculations referred to the top 100 m, the temperature-dependent pressure correction (f_P) was assumed equal to 1. Salinity due to non-ionic species was ignored. Water density was calculated from salinity using the equations of state of Chen and Millero (1977, equation 2, p. 707).

Suspension density (ρ , g·cm⁻³) was determined as:

$$\rho = \text{TSS} + \rho_w(1-\text{TSS})/\rho_s$$

where:

TSS = concentration of suspended sediment (g·cm⁻³),

ρ_w = density of water (g·cm⁻³),

ρ_s = dry density of sediment (assumed = 2.5 g·cm⁻³).

Dry density has not been determined for Lake Malawi and Linthipe River suspended sediments. A sediment density of 2.5 is probably a maximum value, as at least some of the mineral sediment will be lighter. Approximately 10-15% (by weight) of the total sediment load in the Linthipe River is organic matter (based on loss-on-ignition determinations for only 3 samples) with a density of the order of 0.5-1 g·cm⁻³.

Linthipe River

Linthipe River water discharge, temperature, conductivity, TSS and density records are summarised in Figure 1. Overall, Linthipe River water temperature over the period 27 February to 5 March ranged from 25 to 32°C; hence, density due to temperature alone ranged from 0.9970 to 0.9950 g·cm⁻³, or twice the density range encountered in the top 50 m of Lake Malawi (0.9971 to 0.9960 g·cm⁻³, Table 1). Diurnal river temperature fluctuations accounted for half that range, 3 to 4°C, except during periods of relatively cool, cloudy weather (e.g. 24-27 January and the first week in February, when the diurnal range was compressed to under 2°C). The actual density range was even greater, because TSS at the maximum observed concentration added another 0.002 g·cm⁻³ to the river

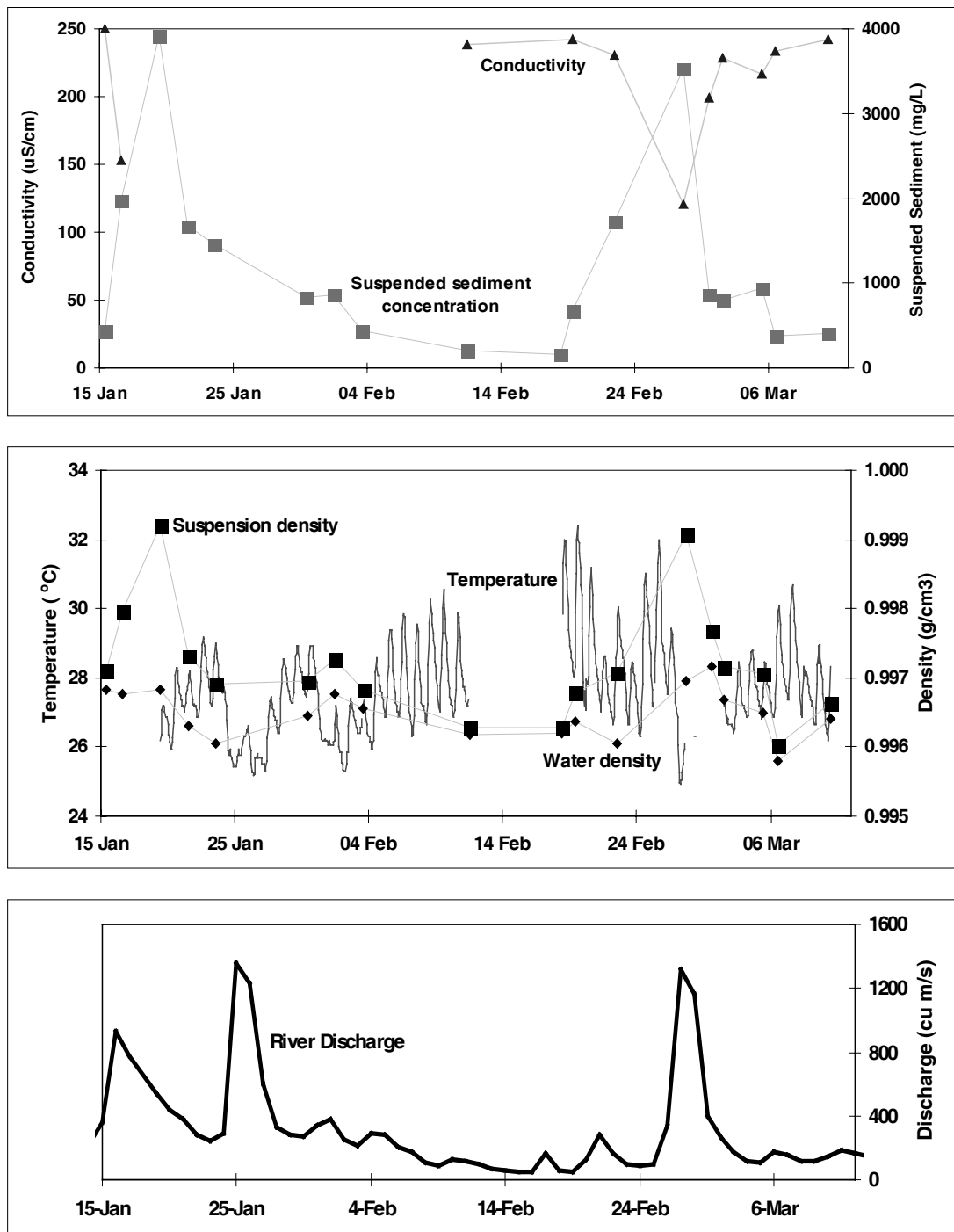


Figure 1. Water discharge (Water Department, Malawi, measured at Salima), temperature, conductivity (adjusted to 20°C), TSS, and water density, total suspension density in the Linthipe River 300 m upstream of Lake Malawi, 15 January to 10 March, 1998. “Water density” (squares) was determined as a function of water temperature and salinity; “suspension density” (diamonds) is in addition a function of TSS.

water density. However, a large fraction of the suspended load – all of the sand and some of the silt – is deposited near the edge of the shoals, and does not contribute to interflow plume density. At the high concentrations measured on 27 February, probably half the load was sand.

Concentration mgL^{-1}	Sand %
100	1
701	30
2680	46

Sediment distribution patterns

The Linthipe River enters Lake Malawi and spreads laterally, forming a subaqueous sand delta out to more than half a kilometre offshore. From the line of the lakeshore, the delta shallows irregularly lakeward, decreasing in depth from 0.5-1 m in the channel upstream to only 0.2-0.5 m along a crescent line of shoals around the mouth. The shoal line is usually marked by highly visible consequences of the meeting of river and lake water. Lake waves break on and mark their outer edge. During high river flow, small (<0.3 m) standing waves run down the thalweg to where it crosses the shoal line, where most of the flow enters the lake. Even this main channel, at the shoals, is less than 0.5 m deep at the shoals, although it is much as 1 m deep back nearer to shore. During the rising and cresting period of storm flows, floating organic debris, mainly reeds, but including corn, sugar cane, banana leaves and tree trunks, collects at the intersection of main channel and lake, forming a slowly rotating (clockwise) mass up to 100-200 m in diameter. Between high flow events, this island of debris is gradually broken up by lake waves, and mostly deposited along beaches to both the north and south.

Depending on river-water density relative to lake water, the edge of the shoals may appear on the surface as a sharp line between turbid, dark red-brown water and pale greenish-brown lake water (if the river water is denser than lake surface water, and therefore plunging) or may be nearly invisible as river water mixes with surface lake water forming a red-brown plume reaching kilometres offshore. Surface plumes spread mostly to south or north (not observed beyond about 10 km offshore to the east), often breaking into patches of varying turbidity which have drifted at least as far as 25 km north of the mouth of the Linthipe. Whether or not a dark surface plume is evident, vertical CTD profiles almost always indicate that river waters bearing higher suspended sediment concentrations plunge along the steeply lakeward-sloping bottom from the shoals into adjacent 20-40 m deep water. At depths where they encounter lake water of equal density, most often at thermoclines or sub-thermoclines creating local high vertical density gradients, these density flows spread laterally out into the lake, where they can be observed as turbidity peaks in CTD profiles up to 10s of kilometres from the river mouth.

Figure 2 illustrates water column profiles of temperature, conductivity, total TSS and density along transects running south-southeast and northeast from the mouth of the Linthipe River. Prior conditions are tabulated below.

SSE Transect, 5 March - At 0.9 km offshore on 5 March, in only 16 m of water, TSS was 100 mgL^{-1} through most of the water column, and $100\text{-}200 \text{ mgL}^{-1}$ in the bottom few metres. River TSS (measured in the river channel 70 minutes earlier) of over 900 mgL^{-1} had been reduced by sedimentation and/or dilution. Only 100 m further offshore, upper water column TSS was reduced to about 10 mgL^{-1} . The peak was less than 100 mgL^{-1} , and no longer followed the lake bottom. Rather, the turbid plume was buoyed by more dense water under a sharp thermal gradient at 26-28 m depth.

In CTD profiles taken beyond 2 km offshore, two turbidity and conductivity anomalies are clearly visible, associated with steep temperature/density gradients near 28 and 36 m deep in the water

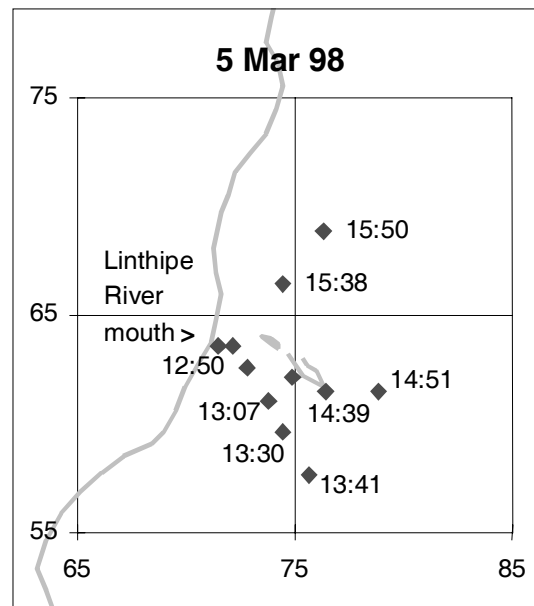
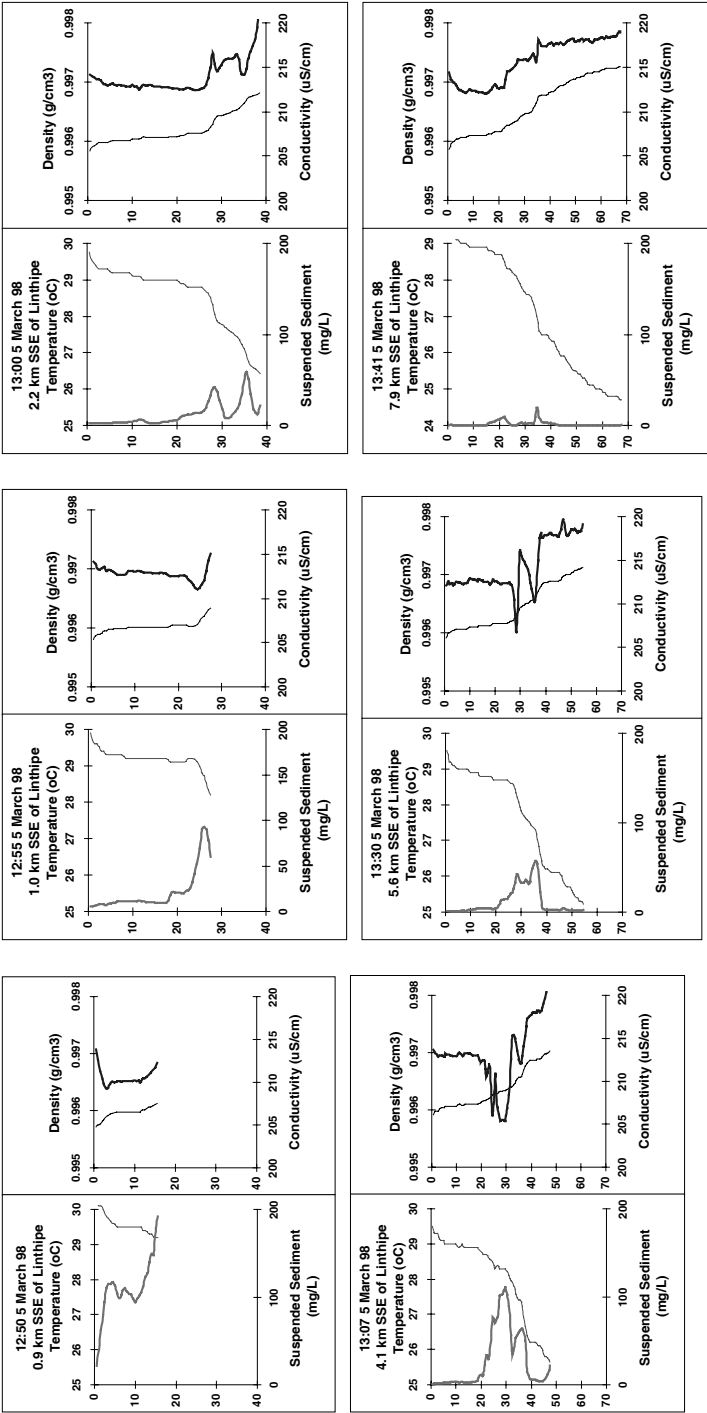


Figure 2. (This page and following 2 pages). Vertical profiles of temperature, density (light lines), TSS and conductivity (heavy lines), 5 March, 1998. Grid is UTM 10 km squares.



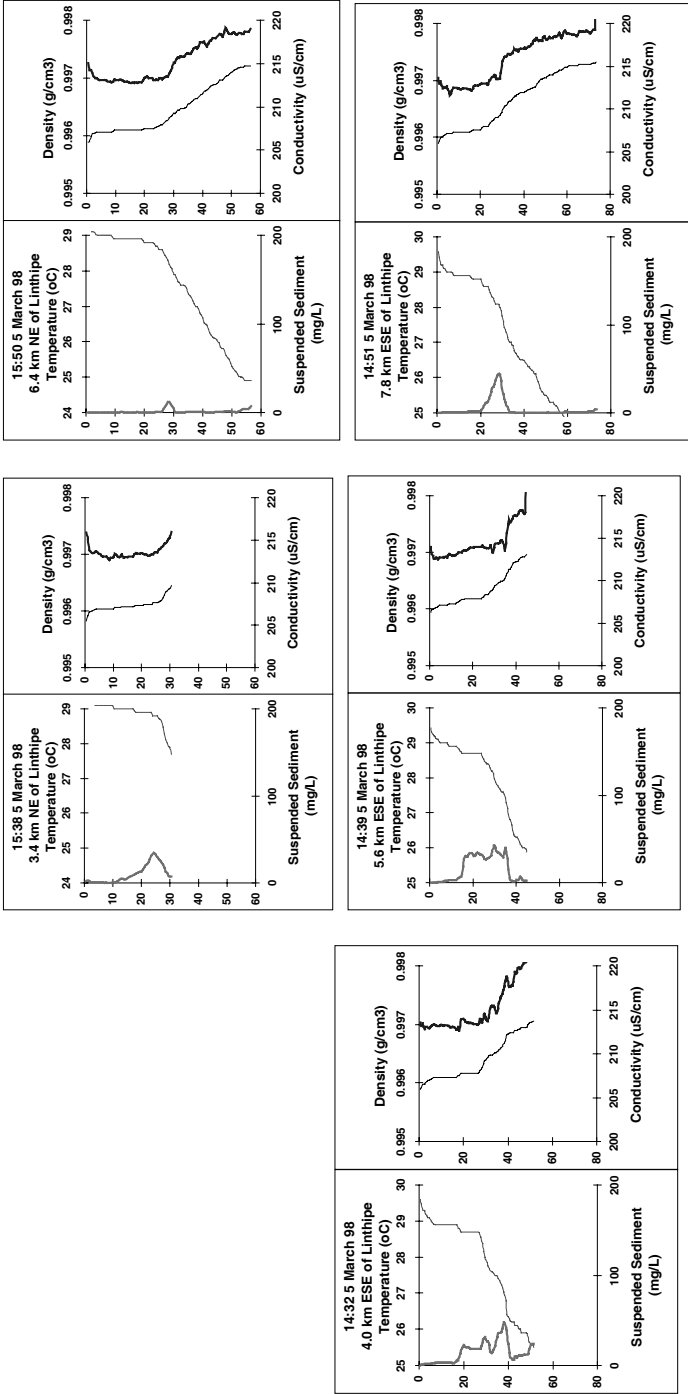


Table 1. Comparison of open lake water densities with Linthipe River water densities.

	Depth m	Temp. °C	Cond. at 20°C uS·cm ⁻¹	Susp. Sediment mg·L ⁻¹	Density ¹ g·cm ⁻³	Density ² g·cm ⁻³
Open Lake						
5 March	0	29.3	215	1.6	0.9960	0.9960
	50	25.2	219	1.6	0.9971	0.9971
Linthipe River						
19 February		28.3	242	677	0.9964	0.9968
22 February		30.0	230	1725	0.0070	0.9971
27 February		25.2	120	3527	0.9970	0.9991
1 March			199	866	0.9972	0.9977
2 March		27.2	228	796	0.9967	0.9972
5 March		27.3	217	937	0.9965	0.6671

Density¹ = density of water calculated from temperature and conductivity data. **Density²** = density of suspension with TSS included in calculation.

column. At 2.2 km offshore, the upper half of the upper TSS peak is associated with a positive conductivity anomaly, indicating that it contains some portion of Linthipe River water of greater than 215 uS·cm⁻¹, i.e. water which entered the lake on or after 2 March. A much higher and broader TSS peak was observed at 28 m depth at 4.1 km, in association with a much larger, but negative conductivity anomaly. The coincidence of a massive layer of very turbid water so far offshore, with the lowest conductivity observed in the lake off the Linthipe mouth on that day, suggests that this water is associated with the water discharge peak, TSS peak, and conductivity minimum that occurred in the Linthipe River on 27, 28 February. At 5.6 km offshore, a layer at about the same depth, marked by a similar conductivity minimum associated with a lower TSS peak, may be associated with an earlier part of the same event. Water in the layer at 28 m depth would have flowed out into the lake to these points at an average rate of 0.6-1.1 km·day⁻¹.

The head of the plume, however, spread into the lake at a considerably higher rate. At 7.8 km, a layer of turbid water (with peak TSS only ¼ as high) at the same depth, not associated with a clear conductivity anomaly, is probably also associated with the same 27, 28 February event. A CTD/O profile recorded on 1 March at 6.2 km SSE (not illustrated, along the same transect as 5 March) showed a small TSS peak (7 mg·L⁻¹) at 20 m depth, while another at 8.2 km offshore indicated almost no significant TSS in the water column and none in the 20-40 m depth range. Since the river first peaked on 27 February, the head of the interflow plume had to have spread outwards to at least 6 km offshore at about 3 km·day⁻¹.

At 2.2 km offshore, where the turbid layer at 28 m depth appears to be post-2 March river water, the lower TSS peak, at 36 m deep, contains water delivered to the lake when river conductivity was less than 215 uS·cm⁻¹, i.e. on or before 1 March. The turbid layer seems contiguous across stations 2.2, 4.1, 5.6 and 7.9 km, in every instance associated with a negative temperature anomaly, and probably is throughout associated with the 27, 28 February high flow event. That the upper turbid layer at 2.2 km has apparently arrived from the river more recently than water in the lower turbid layer may be related to the gradually warming trend in the river after 27 February. That is, newer (warmer, less dense) water may be pushing out into the lake only along the shallower thermocline. If that is so, then incoming flow is the dominant force controlling short term movement of Linthipe River water and its sediment load out into Lake Malawi.

ESE, NE Transects, 5 March - The east-southeast transect is similar in general form to the south-southeast transect, except in that at the furthest offshore station observed, 7.8 km from the mouth of the Linthipe, the peak TSS is almost $50 \text{ mg}\cdot\text{L}^{-1}$ in a turbid layer about 10 m thick, both thicker and more than twice as turbid as at the same distance offshore to the south-southeast. However, at a similar distance to the northeast, 6.4 km from the Linthipe, the same layer is less than 5 m thick with a peak TSS of $12 \text{ mg}\cdot\text{L}^{-1}$. At 3.4 km northeast, the peak TSS is $35 \text{ mg}\cdot\text{L}^{-1}$, considerably less than at similar distances offshore to the southeast. Flow northward is constrained to some extent by the Maleri Islands and the associated underwater ridge extending almost 10 km south-eastward into the lake. The passage between Nankoma Island (the nearest island to the mainland) and the mainland is only about 35 m deep, and between Maleri and Nankoma, less than 20 m. Hence, only that portion of river discharge that mixes with shallow surface waters or that flows along the bottom directly north-eastward from the river mouth is readily dispersed northward. It seems likely that the greater part of those Linthipe River sediments transported in interflow are transported first to the southeast, and must pass to the south of Maleri Island before being dispersed northward.

Temporal record at 4 km Offshore, SSE Transect, 21 January - 10 March - Figure 3 is a time series of vertical temperature and TSS profiles all located at about 4 km offshore along the same southeast transect as shown in Figure 2. The horizontal scale for suspended sediment concentration is enlarged for 27 February and 1, 5 March relative to the others.

Generally, a thermocline was observed at about 35–45 m depth, but strong temperature gradients which formed at various times above this relatively permanent feature often controlled the depth of interflow turbid Linthipe River water. On 21 January, a TSS maximum of $40 \text{ mg}\cdot\text{L}^{-1}$ was observed in association with a strong temperature gradient at only 8–10 m depth. By 23 January, only a much less turbid layer remained, creating a small TSS peak at about 18 m depth; the thermal gradient of two days earlier had been eroded from 8–10 m down to 21–22 m depth. By 26 January, when a new pair of strong TSS peaks developed in response to the high river discharge of 25, 26 January, the 20 m thermal gradient was very weak. Furthermore, the minimum river water temperature associated with this storm peak was low enough that the density (before any mixing occurred with lake water) was considerably greater than the maximum density in the water column at the sample station. Turbid layers were observed in deeper water further offshore on 27 January at 47 m depth. In the month between major storm flow events, only small TSS peaks were observed in the water column, with the exception of the 11 February sample, in which a $20 \text{ mg}\cdot\text{L}^{-1}$ TSS maximum was recorded at the thermocline (40 m depth). Then the high river discharges of 27, 28 February created a massive layer of turbid water, with a peak concentration of more than $300 \text{ mg}\cdot\text{L}^{-1}$, and a thickness of 20 m, from 20 to 40 m depth in the water column. The 5 March profile shows essentially the same thick layer, by then reduced to a still very turbid maximum of $100 \text{ mg}\cdot\text{L}^{-1}$. The quite differently shaped profile of 1 March is turbid at 20 m and 36–42 m, but nearly clear between. The separation into two layers appears to be associated with the development of a thermal gradient at 20 m that did not exist on 27 February and which had largely eroded by the following day. On 10 March, sediment is concentrated in a thin layer on a strong thermal gradient at 22 m depth, and peak TSS was reduced to less than $30 \text{ mg}\cdot\text{L}^{-1}$.

Sediment load

An estimate was made of total sediment load in Lake Malawi in the vicinity of the Linthipe River for two occasions for which large CTD profile sets were available following the February 27–28 storm flow event (Table 2). For each estimate, data was pooled from profiles measured on two consecutive days. Stations used to create the data sets are shown in Figure 4. On each occasion, CTD/O profiles were obtained along six transects radiating outwards from the mouth of the Linthipe River, to distances of about 10 km. Mean sediment load per square metre for 10-metre depth intervals was calculated for each sample profile. For each depth range, values were estimated for points on a 1-km square grid by linear distance-weighted averaging of values for the nearest measured profile in each

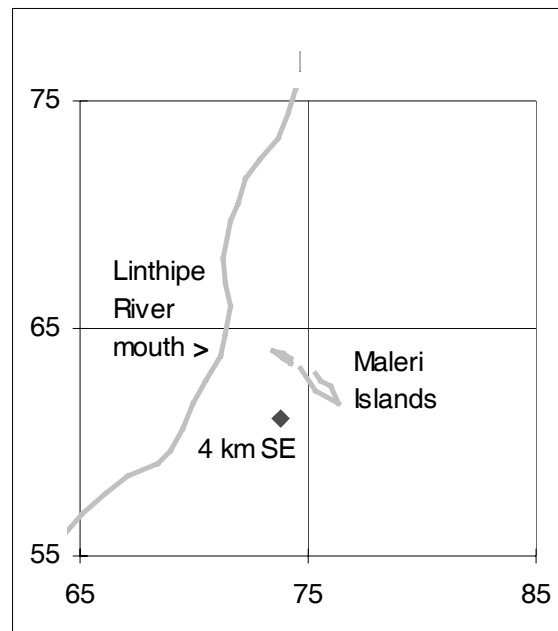
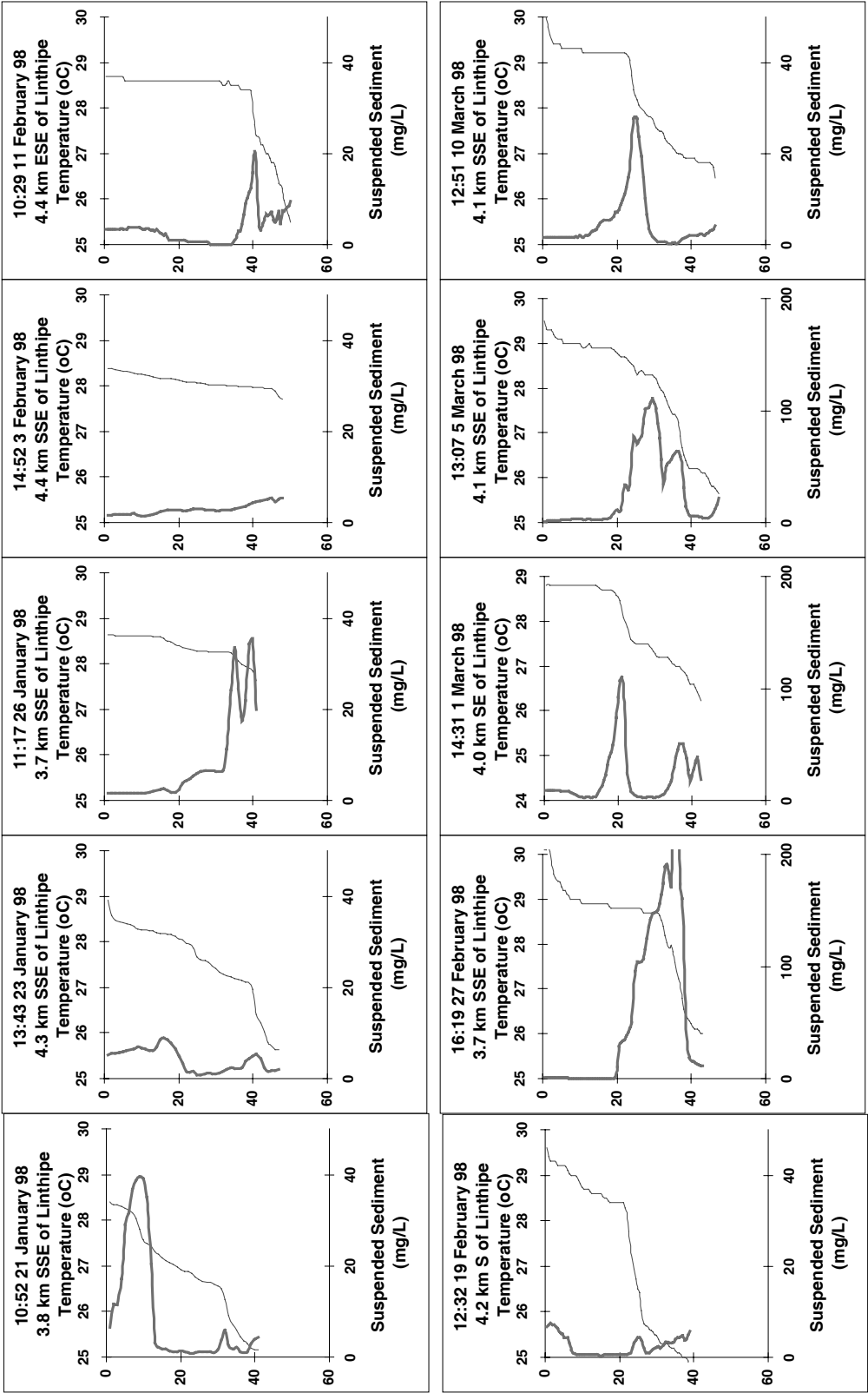


Figure 3. Vertical profiles of temperature (light lines) and TSS (heavy lines), 4 km SE of the Linthipe River mouth, January-March 1998. Illustrated on following page. Grid is UTM 10 km squares.



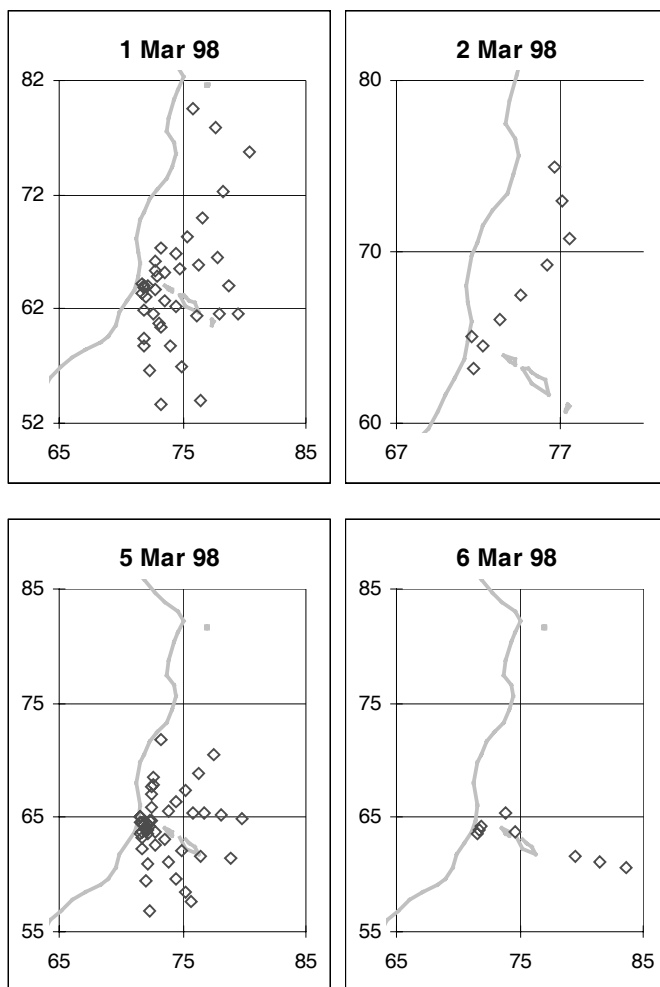


Figure 4. Stations used to estimate the total sediment load in Lake Malawi in the vicinity of the Linthipe River on 1,2 March and 5,6 March. Grid is UTM 10 km squares.

quadrant around the grid point. The values reported below are the sum of all grid values within 10 km of the mouth of the Linthipe River. Column 2 records the area of lake for each depth range within 10 km of the river mouth, based on the Linthipe delta bathymetric map of Johnson et al (1995). The choice of a 10 km radius is an artefact of sampling limitations. Significant but poorly documented amounts of sediment were certainly carried beyond 10 km from the river.

Table 2. Total sediment load in the lake near the mouth of the Linthipe River following a large storm flow event.

depth m	area km ²	1,2 March tonnes	5,6 March tonnes
0-10	183	10294	10290
10-20	183	22087	9178
20-30	147	35585	18776
30-40	120	13701	9313
>40	115	4205	2621
sum		85872	50178

Two-thirds of the sediment observed was carried in interflow along thermal/density gradients corresponding to the profile TSS peaks at about 28 and 36-40 m depth (Figure 2). Although offshore transects extended to regions as deep as 100 m, only a small fraction, about 5%, of sediment in transport was observed in the water column below 40 m depth.

From 26-28 February, the Linthipe River delivered of the order of 700 000 tonnes of suspended sediment to Lake Malawi. Only about 1/10 of this amount was observed in the water column within 10 km of the river mouth three days after the flow peaked. Much of this difference was due to sedimentation of coarse particles. As much as half of the load was sand, which would have been deposited within a few hundred metres of the nearshore shoals. An unknown additional fraction of coarse silt would also have settled out within hours or days. About half the load observed between 10-30 m depth on 1,2 March was lost by 5,6 March. The peak sediment load in the 10-30 m depth strata on 1,2 March was located within 4-5 km of the river mouth. Hence, the losses in the next few days were likely due more to settling out of coarser particles than to the other logical possibility, lateral transport beyond the 10 km radius sampled. That 1,2 March sediment levels persisted in the upper 10 m may be explained either by a lower overall settling rate or by resupply as post-storm, warmer river water mixed preferentially with lake surface water.

Conclusions

Transport and deposition of the Linthipe River suspended sediment load after it is delivered to Lake Malawi is dependent on particle size distribution and the interplay of river temperature and the vertical temperature structure of the lake. A large, currently unknown fraction of the suspended river load is sand and coarse silt which settle out quickly as river velocity and turbulence are diminished in the lake. The subaqueous delta reaching several hundred metres offshore from the mouth of the river is a product of that first, rapid deposition of coarse material. Although suspended sediment contributes greatly to in-river density, so much sediment is lost so quickly that it has little effect on the ultimate depth in the lake at which river water finds neutral buoyancy.

River temperatures measured from January to March ranged from as high as the highest lake temperature measured during the same period, down to within a degree of the coolest measured below

the thermocline. Although the visible surface plumes resulting from surface mixing of warm river water are, of course, more apparent, most river water apparently plunges to depths of neutral buoyancy, which are almost always associated with sharp density gradients of thermoclines and sub-thermoclines.

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