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Suspended Sediments in Lake Malawi, Africa: A Reconnaissance Study

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ABSTRACT. *In order to investigate the source and distributional pathways of suspended sediment in a tropical rift-valley lake, water-column profiles of light transmission (inversely related to water turbidity) were coupled with filtered water samples to determine total suspended sediment (TSS) concentrations at 28 stations throughout Lake Malawi (Lake Nyasa), East Africa, during January, 1992. TSS concentrations of the water column are typically between 0.1 and 0.5 mg/L, lower than those reported for the lower Laurentian Great Lakes. Elevated levels of turbidity are detected both at stations near the shoreline and offshore at four depths: at or near the surface, at the lake floor, at the chemocline, and in a mid-depth layer that is unique to the stations offshore of the Ruhuhu Delta. The latter had the most turbid water detected on this cruise and is interpreted as an interflow injection of fluvial material related to a 2-day rainstorm. Estimates suggest that this event contributed a significant portion of the annual sediment load to the delta. Other important sources of suspended sediment in Lake Malawi probably include biological productivity at the surface, chemical or biological processes at the chemocline, and resuspension events produced by wind-induced waves and currents and by seiche activity.*

INDEX WORDS: *Suspended sediments, Lake Malawi, sediment transport.*

INTRODUCTION

The role of suspended matter in reservoirs, lakes, and oceans has received an increasing amount of attention in recent years. Suspended matter, by virtue of its presence, composition, and movement within the water column, is responsible for maintaining concentration gradients of many chemical species including pollutants (e.g., Biscaye and Eittreim 1977, Eisenreich and Long 1989, Prior and Bornhold 1989). Despite its importance, our understanding of suspended sediment processes in lacustrine settings is still poor.

Investigations of suspended matter in lacustrine systems, especially large lakes, have been predominantly in lakes of the northern temperate zone. Persistent deep-water nepheloid layers, i.e., intervals in the water column with relatively higher concentrations of suspended particulates, were reported from Lakes Michigan and Superior (Chambers and Eadie 1981, Halfman and Johnson 1989), and prompted additional characterization of their composition and dynamics (e.g., Eisenreich and Long 1989, Mudroch and Mudroch 1992). Other studies revealed that hypopycnal (surface), intermediate (interflows), and hyperpycnal (e.g., turbidity currents) pathways are also important for suspended sediment transport (Smith 1978, Giovanoli 1990).

Recent seismic profiling and sediment coring of the large tropical rift lakes in East Africa has revealed a complex history of sedimentation; i.e., widely disparate sedimentary facies occur in close juxtaposition (Crossley 1984, Scholz *et al.* 1990, Johnson and Ng'ang'a 1990). These studies underscore the critical need to understand the factors that influence sedimentation, e.g., tectonic and climatic setting, biological productivity, and water chemistry. This paper presents profiles of total suspended sediment concentrations through the water column in Lake Malawi during January, 1992, as detected by light transmissometer. Our goal is to provide a preliminary description of the sources to and distribution patterns of suspended matter in a tropical rift lake.

LAKE MALAWI

Lake Malawi (Lake Nyasa), located at the southern end of the East African Rift System, is the fifth largest lake in the world by volume (Fig. 1). It is approximately 570 by 75 km with mean and maximum depths of approximately 200 and 700 m, respectively. The hydrological budget is primarily controlled by precipitation, river runoff, and evaporation (Beadle 1981). The Shire River, at the southern end of the lake, presently accounts for 20% of the water loss although the lake has been closed during historic and earlier episodes (Beadle 1981, Scholz and Rosendahl 1988). Seasonal patterns in climate are observed at the lake. A rainy, slightly warmer season during austral summer (December to March) is followed by a windy, slightly cooler season during austral winter (May to October).

In contrast to lakes in temporate climates, Lake Malawi is meromictic, i.e., only the upper portion of the water column mixes during austral winter (Eccles 1974). The mixolimnion (upper, mixed layer) is oxygenated and experiences seasonal variability in surface temperature (23 to 29°C) associated with the seasonal growth and destruction of a thermocline at approximately 100 m. The monimolimnion (lower, unmixed layer) is anoxic and isothermal (22.7°C). Previously, temperature was believed to be the primary control for meromixis, i.e., surface-water temperatures never cool below monimolimnion temperatures to induce deeper mixing; however, recent conductivity profiles in conjunction with measurements of dissolved silica indicate that the dissolved constituents are also important at maintaining meromixis (Halfman 1993). The boundary between the mixolimnion and monimolimnion defines the chemocline at approximately 200 m.

The modern sediments are dominated by nearshore sands that extend out to water depths of 100 m (Johnson and Ng'ang'a 1990, Scholz *et al.* 1990, Pilskaln and Johnson 1991). The profundal sediments are commonly laminated, organic- and diatom-rich, clayey silts or silty clays. Occasional sandy channels adjacent to deltaic systems are the exception. They are presumably maintained by turbidity currents even in the deepest portions of the lake. Mean sedimentation rates in the profundal sediments range from approximately 1 to 3.5 mm/yr; and, mass accumulation rates are approximately 20–50 mg/cm^2/yr based on water content, ^{210}Pb and ^{14}C profiles (Johnson and Ng'ang'a 1990, Owen *et al.* 1990, Finney and Johnson 1991).

The morphology of the lake floor is primarily controlled by rift tectonics. Lake Malawi is segmented into four half-graben basins that tend to alternate dip polarity along the axis of the rift (Specht and Rosendahl 1989). The tectonics subdivides the lake floor into border-fault margins that are set opposite to shoaling margins. The lake floor dips (9° or more) steeply and directly to the deepest basins in the lake at the former and is less steep (1.5° dip) at the latter.

METHODS

The distribution and relative concentration of suspended sediment in the water column was investigated at 28 stations in Lake Malawi during January, 1992 using a light transmissometer (Sea Tech, Inc., TR2025) with a 25-cm pathlength. Station locations were primarily offshore of three deltaic systems associated with the Ruhuhu (RH), Dwangwa (DW), and Linthipe (LN) rivers, but we also occupied four Mid-Lake (ML) sites (Table 1, Fig. 1). The deltaic systems were selected to represent the range of tectonic settings (Linthipe on a shoaling margin and Ruhuhu on a border-fault margin) and the range of exposure to winds and associated waves and currents (Linthipe relatively protected and Dwangwa relatively exposed). All of the rivers have approximately the same drainage basin size and mean annual discharge rates (Table 1). At each delta, individual stations were selected to coincide with turbidity channels, thick accumulations of sediment, or other features based on field interpretations of high-resolution seismic profiles that were collected during the same cruise. Satellite navigation (GPS) and on one occasion a radar fix (when satellites were not available) provided positioning information. Accuracy was better than ±15 m for the GPS fixes.

Each transmissometer cast was from the surface to approximately 10 m above the lake floor with a few casts to the lake floor. The transmissometer

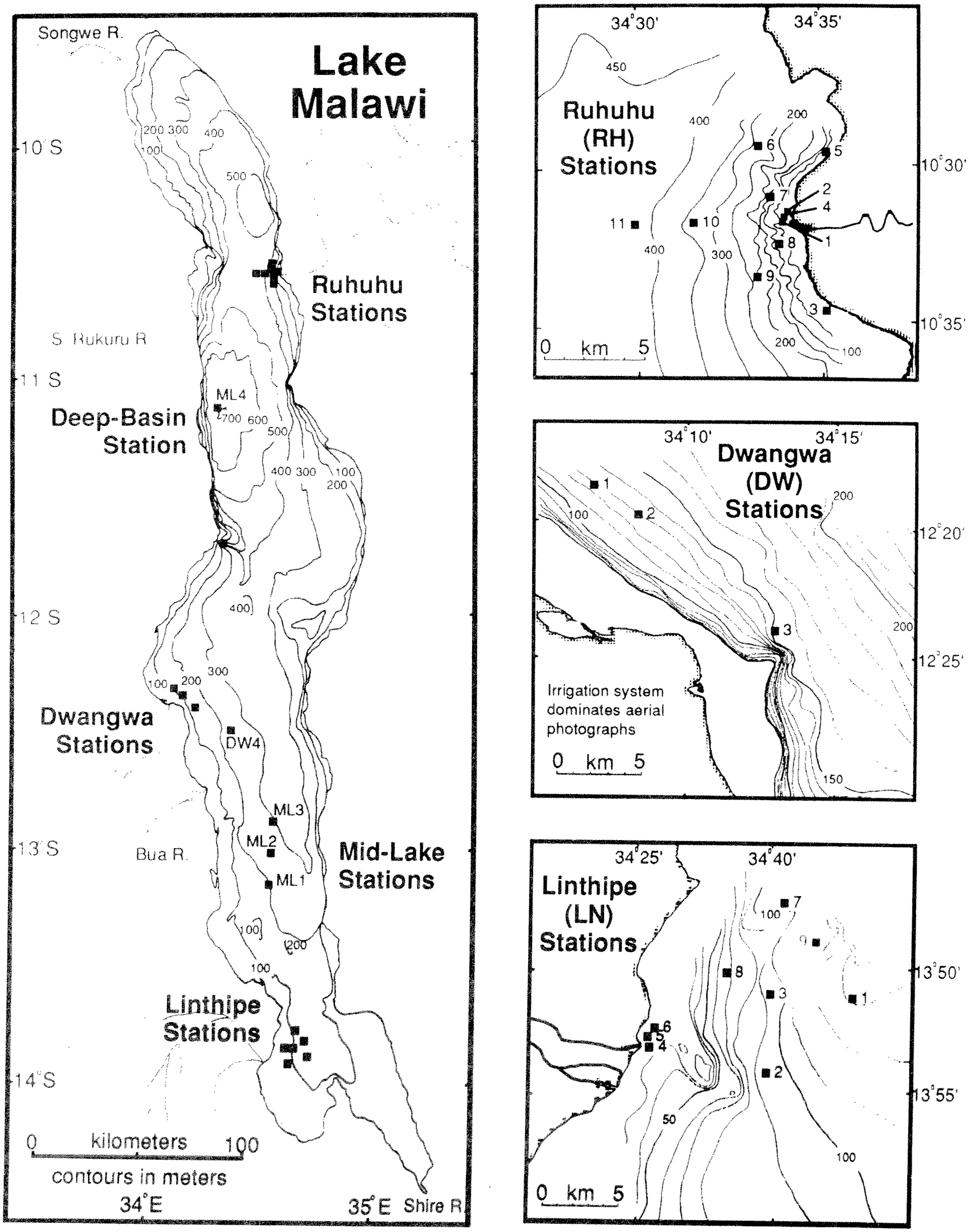


FIG. 1. Station location and bathymetric map of Lake Malawi (Lake Nyasa) with detailed maps of the Linthipe, Dwangwa, and Ruhuhu deltas, the three deltas in this survey. River locations are transcribed from modern aerial photographs. Note the change in contour interval and scale between maps.

TABLE 1. Station information and key physical parameters of rivers.

Region Station ID	Latitude	Longitude	Distance River Mouth (km)	Depth (m)	Date Profiled	TSS Concentration (mg/L) Avg	Max	Min
Linthipe								
LN1	13°51.47'S	34°42.89'E	13.4	133	16 Jan 92	0.45	1.5	0.25
LN2	13°54.28'S	34°39.87'E	8.0	93	16 Jan 92	0.45	0.87	0.25
LN3	13°51.00'S	34°39.89'E	8.6	91	16 Jan 92	0.50	0.98	0.30
LN4	13°53.08'S	34°35.61'E	0.1	5	17 Jan 92	9.0	16	5.8
LN5	13°52.89'S	34°35.66'E	0.4	5	17 Jan 92	2.4	3.7	2.2
LN6	13°52.73'S	34°35.75'E	0.7	5	17 Jan 92	2.4	3.3	2.1
LN7	13°47.37'S	34°40.52'E	13.8	110	17 Jan 92	0.50	1.2	0.25
LN8	13°50.03'S	34°38.47'E	7.6	69	17 Jan 92	0.65	1.8	0.35
LN9	13°48.92'S	34°41.78'E	13.5	117	17 Jan 92	0.45	1.0	0.25
Dwangwa								
DW1	12°18.84'S	34°07.04'E	8.7	127	23 Jan 92	0.35	0.87	0.21
DW2	12°19.92'S	34°08.34'E	6.8	130	23 Jan 92	0.35	1.1	0.21
DW3	12°24.00'S	34°12.90'E	9.8	152	23 Jan 92	0.35	0.60	0.21
DW4	12°30.57'S	34°21.66'E	28.8	236	23 Jan 92	0.25	0.50	0.21
Ruhuhu								
RH1 [a]	10°31.9'S	34°34.0'E	0.3	4	29 Jan 92	0.92	0.98	0.87
RH2	10°31.47'S	34°33.85'E	0.6	4	29 Jan 92	2.8	2.8	2.7
RH3	10°34.85'S	34°35.20'E	6.2	5	29 Jan 92	1.0	1.0	1.0
RH4	10°31.78'S	34°33.86'E	0.1	78	29 Jan 92	4.4	32 [d]	0.50
RH5	10°28.73'S	34°35.31'E	6.2	4	29 Jan 92	1.9	6.4	0.98
RH6	10°29.76'S	34°33.42'E	3.8	289	29 Jan 92	0.45	1.1	0.30
RH7	10°30.95'S	34°33.62'E	1.6	140	29 Jan 92	0.70	2.6	0.40
RH8	10°32.50'S	34°33.69'E	1.4	73	29 Jan 92	2.9	2.3	0.69
RH9	10°33.56'S	34°33.15'E	3.5	225	29 Jan 92	0.26	13	0.30
RH10	10°31.75'S	34°31.65'E	4.0	331	29 Jan 92	0.70	16	0.25
RH11	10°31.94'S	34°29.91'E	7.2	407	29 Jan 92	0.45	11	0.25
Mid-Lake								
ML1	13°10.02'S	34°32.07'E	na	201	19 Jan 92	0.35	0.92	0.21
ML2	13°01.31'S	34°32.86'E	na	250	19 Jan 92	0.25	0.45	0.21
ML3	12°53.48'S	34°33.76'E	na	302	19 Jan 92	0.21	0.45	0.16
ML4 [b]	11°10.00'S	34°20.00'E	na	690	24 Jan 92	0.30	0.50	0.25

River Data[c]	Annual Discharge (m^3/s)	Drainage Size (km^2)	Wave Energy	Offshore Slope
Ruhuhu	40	17,230	High	3-7°
Linthipe	36	8,640	Low	0.5°
Dwangwa	21	7,770	Moderate	0.5 - 3°

[a] Navigation by radar
[b] Two casts at this station
[c] from Scholz *et al.* 1993
[d] Exceeded the detection limit of the transmissometer

was calibrated to a free-air light transmission of 100% and blocked path transmission of 0%. The instrument was electronically linked to a SEACAT CTD (Sea-Bird Electronics, Inc., SBE-19 interfaced with SBE-23Y polarographic oxygen sensor) that internally recorded conductivity, temperature, depth, and dissolved oxygen data, and later downloaded the data to an IBM-compatible computer. Data reproducibility for the transmissometer was 0.5 transmission units (on a scale of 0 to 100), and was computed by calculating the average difference between the up-cast and down-cast data along 0.5 m intervals at each station after adjusting the up-cast depth to reflect the depth-offset between the transmissometer and the pressure transducer. The reproducibility of a multiple cast to water depths just over 200 m at ML4, the deepest station, is 0.4 transmission units. The results of the CTD profiles are reported elsewhere (Halfman 1993).

Water samples for total suspended solids (TSS) were obtained with a Wildco Beta Plus 2.2 L horizontal water sampler from either 2 or 3 m below the surface. Total suspended solids concentrations were determined in duplicate and on one occasion in triplicate by filtering 2 to 3 L of lake water under vacuum through a precombusted (550°C-1 hour), preweighed Gelman glass fiber filter (A/E, 1.0 μm nominal pore diameter), followed by freeze drying and reweighing in the laboratory. The uncertainty in TSS concentrations was 0.1 mg/L, and was computed by calculating the average deviation from the mean of all replicate filters.

Percent light transmission was empirically related to TSS concentrations using a least-squares, linear regression of the mean TSS concentration from the filtered water samples (mg/L) and light attenuation {attenuation, $m^{-1} = -\ln(T)/0.25$, where T is the percent light transmitted over a distance of 0.25 m} at the depth of the water sample (Fig. 2). The resulting equation (Eq. 1) was:

$$\mathrm{TSS} = 1.02\,\{\mathrm{attenuation}\} - 0.362 \qquad r^2 = 0.98,$$

where TSS is the concentration of total suspended solids in mg/L. The error estimate (r^2) does not include errors revealed by multiple filters and multiple casts. For the TSS profiles presented here, we assumed that the empirical relationship determined for the surface waters is applicable throughout the water column and over the range of transmission values detected on the cruise (see additional comments below).

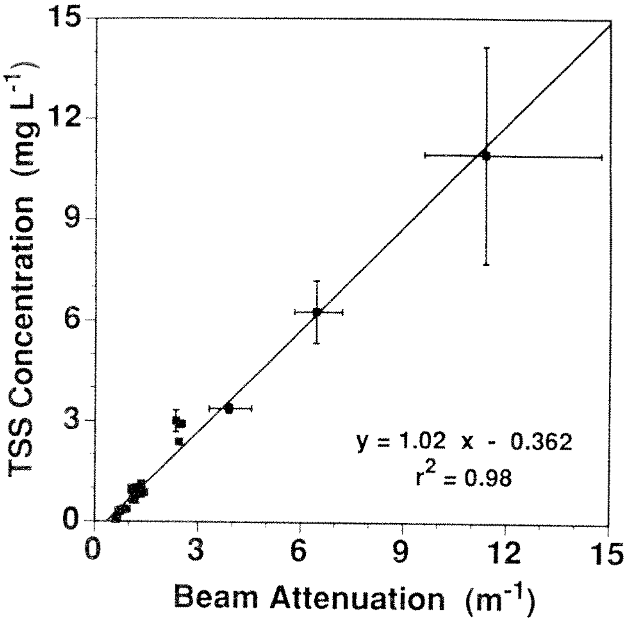
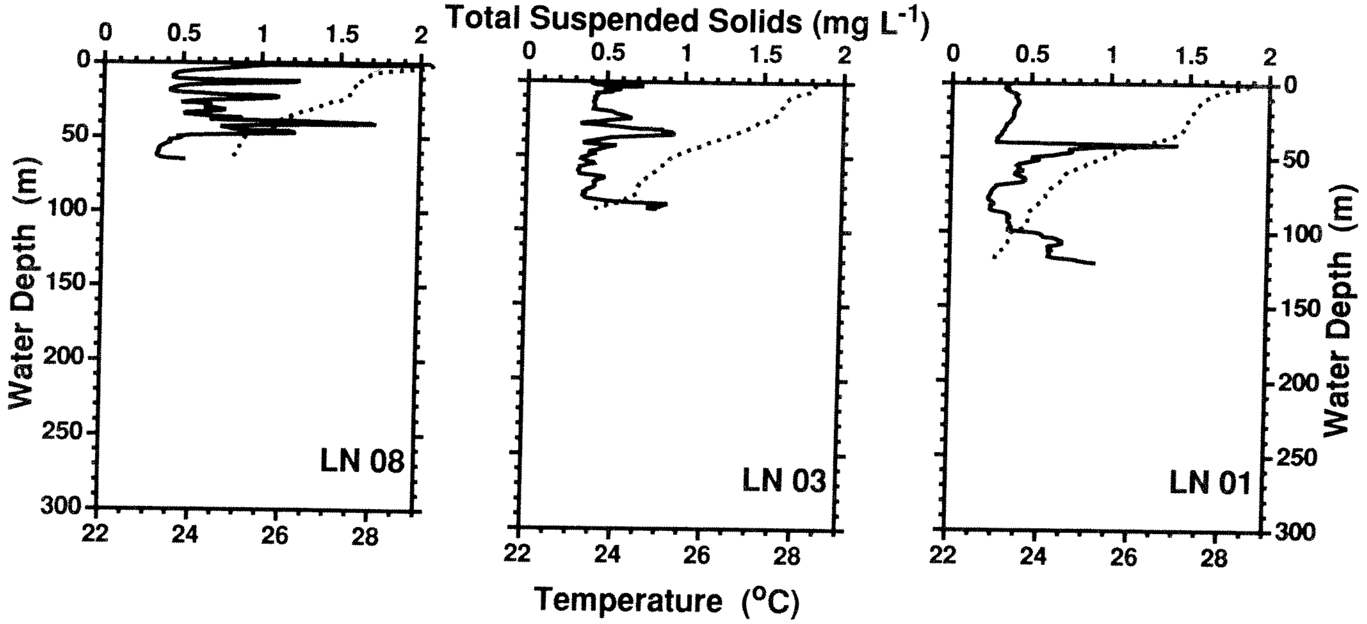


FIG. 2. A least-squares, linear regression between total suspended solid concentrations measured in the field and light attenuation of the transmissometer at the depth of the water sample (see text for details).

RESULTS

Total suspended solid concentrations in Lake Malawi range from 0.1 mg/L to levels above the upper detection limit of the transmissometer. The average TSS concentration at 15 of the 21 offshore stations (stations with water depths > 50 m) is between 0.1 to 0.5 mg/L, with the lowest turbidity detected at these sites between 0.10 and 0.35 mg/L (Table 1, Fig. 3). These average values are at the low end of the spectrum and are within the calibrated range of the transmissometer (Fig. 2). However, Eq. 1 is less reliable at turbidities greater than about 5 mg/L due to a lack of surface sites with TSS concentrations above 5 mg/L, and large changes in turbidity (>5 mg/L) over short depth intervals (<0.5 m) at the sites with high turbidity. Despite these difficulties, the relationship is interpreted as a reliable indicator of the TSS data reported here because: (1) the slope of the regression is near one and the extrapolated light attenuation for particle-free water is 0.354 m^{-1} - both criteria are within two orders of magnitude of commonly reported values for laboratory calibration tests of transmissometers (e.g., Spinrad 1986);

(a) Linthipe Sites



(b) Dwangwa Sites

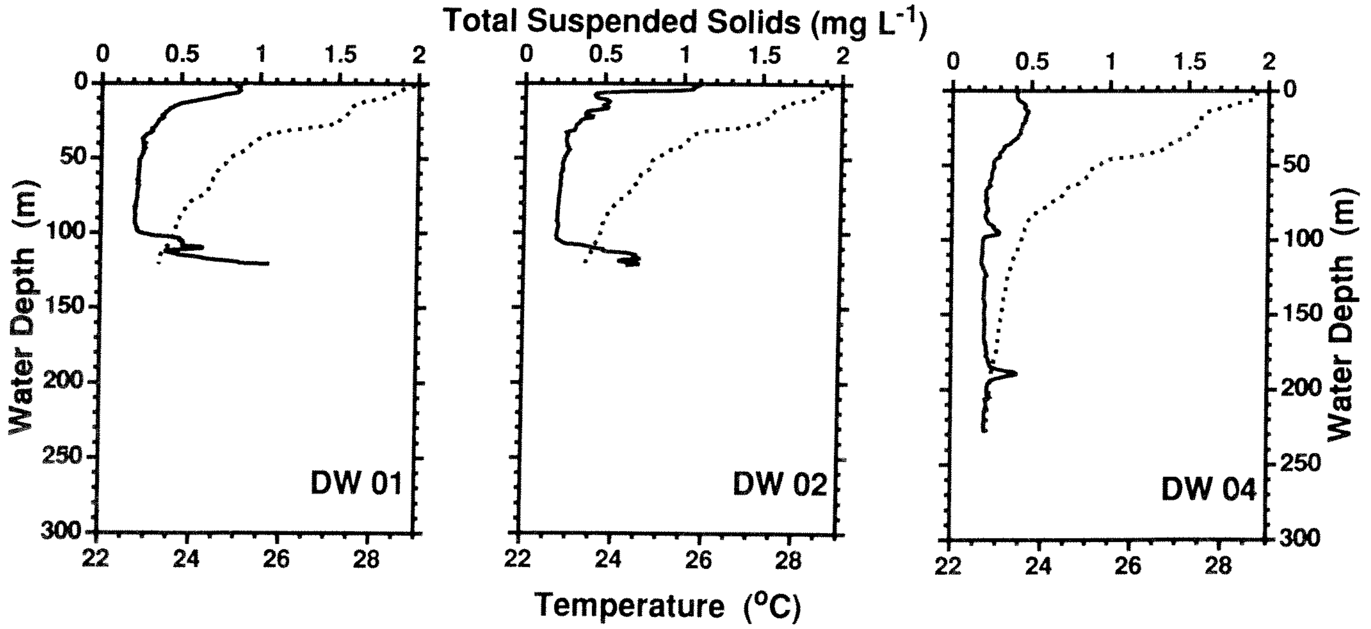
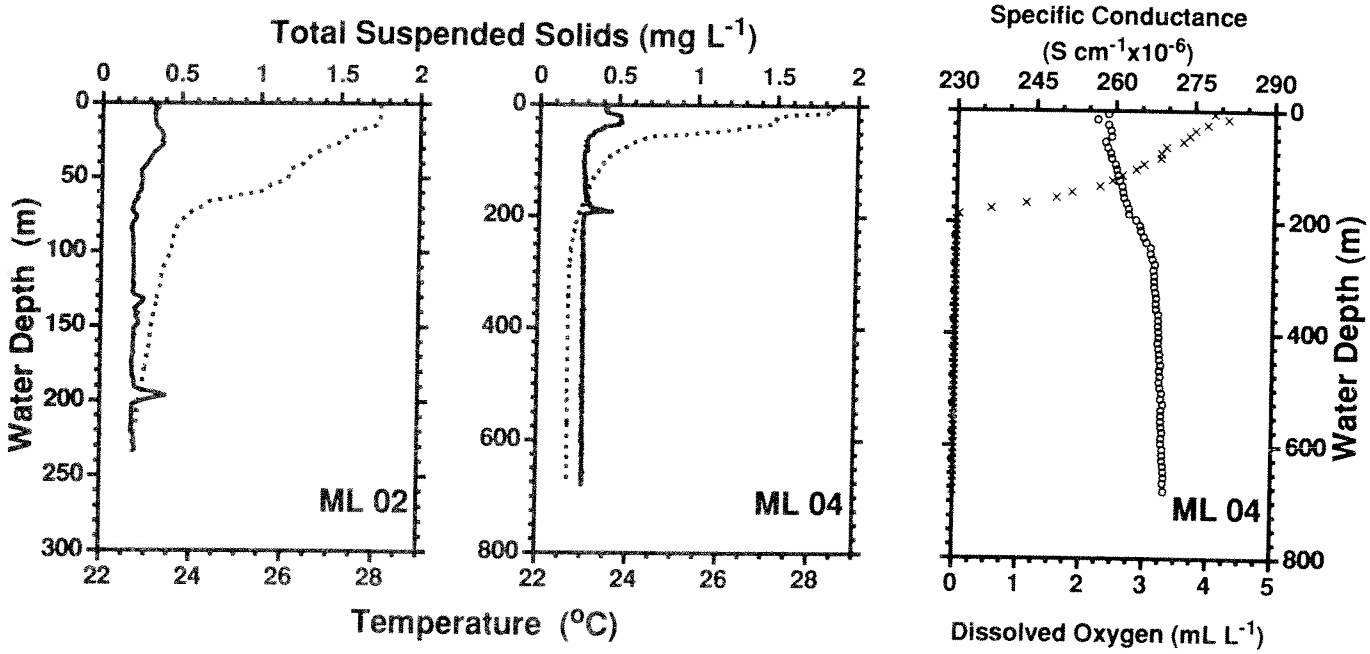
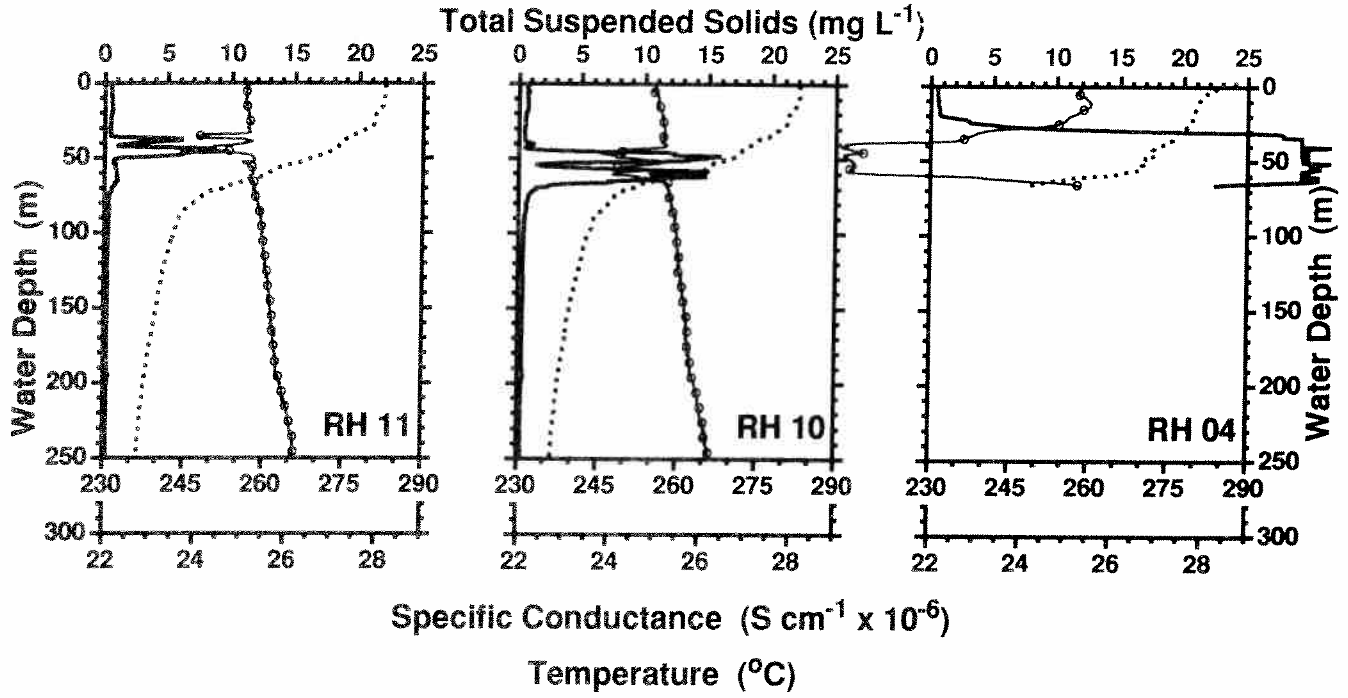


FIG. 3. Representative profiles of total suspended solids (solid line) and temperature (dotted line) through the water column to approximately 10 m above the lake floor and occasionally to the lake floor. Total suspended solid concentrations were estimated from percent light transmission data (Fig. 2). Station locations are shown in Figure 1. (a) Representative profiles offshore of the Linthipe River. (b) Representative profiles offshore of

(c) Mid-Lake Sites



(d) Ruhuhu Sites



the Dwangwa River. (c) Representative profiles at Mid-Lake sites. Specific conductance (circles) and up-cast dissolved oxygen (crosses) profiles at ML4 are representative of the entire lake except for stations offshore of the Ruhuhu River (Halfman 1993). (d) Representative profiles offshore of the Ruhuhu River. Specific conductance and dissolved oxygen profiles are redrawn from Halfman (1993).

(2) the data that plot above the straight-line fit are restricted to nearshore sites (water depths <5 m) and suggest that the variability in TSS, due to the change in light attenuation from potentially unique sediment populations, approximates the variability reported above for the transmissometer and filtered TSS concentrations; (3) additional laboratory calibrations of the transmissometer using diatomaceous earth are consistent with these results; and, (4) the majority of the TSS values reported here are are within the constrained (0.1 to 5 mg/L) portion of the curve.

The distribution of site-averaged turbidity divides into two populations: nearshore stations with TSS values >1 mg/L and offshore stations with TSS values typically <0.5 mg/L. A station offshore of the Ruhuhu River (RH8) is the exception to this trend with detected average TSS values of 2.9 mg/L; however, a mid-depth turbid layer accounts for the apparent anomaly. Among the nearshore stations, the maximum turbidity is detected closest to the river mouth. For example, stations RH4 and LN4 are closest to the respective river mouth and reveal the highest average turbidities (4.4 and 9.0 mg/L, respectively). Among the offshore sites, the site-averaged concentration decreases between stations offshore of the Linthipe River (0.45 to 0.65 mg/L) and stations to the north (0.2 to 0.35 mg/L) that parallels a increase in station water depth. At each delta, spatial trends in the average turbidity are observed within the stations that are offshore of the Ruhuhu River (see below); however, spatial trends are not observed within the stations offshore of the Linthipe and Dwangwa Rivers but the absence may be due to the low density of stations.

Water-column profiles of turbidity typically reveal an increase in TSS above a background level that are restricted to a number of discrete depths (Fig. 3). At the seven nearshore sites (not shown), discrete turbid layers, if present, are typically a meter thick, restricted to the surface and just above the lake floor, and reveal an increase in TSS concentration of 1 to 15 mg/L above the minimum value at the site. The variability in turbidity with water depth decreases with increasing distance from the river mouth. At the 21 offshore sites (only representative profiles shown), turbid intervals are typically 10 to 30 m thick and are usually detected at or near the surface (a turbid layer within the upper 50 m), at the lake floor (up to 30 m above the lake floor), at or just above the chemocline (180 to 200 m), and a mid-depth layer (30–65 m) unique to stations offshore the Ruhuhu River.

The spatial characteristics of the upper turbid layer varies in the lake. A near-surface layer of uniform turbidity (up to 1.1 mg/L) separates less turbid water above and below at the Mid-Lake stations (Fig. 3c, ML1, 2, 3, & 4, ML1 & 3 not shown) and the two deepest stations off the Dwangwa River (Fig. 3b, DW3 & 4, DW4 not shown). Yet the turbid layer is at the surface of the lake at the remaining Dwangwa (DW1 & 2) sites (Fig. 3b). At all of these locations, the boundaries of the layer are associated with steps in the thermocline. The profiles offshore of the Linthipe River (LN1, 2, 3, 7, 8, & 9) reveal a number of discrete spikes in turbidity, each spanning about 10 m of the water column (Fig. 3a). Each spike is about 0.5 to 1.2 mg/L more turbid than the water immediately above and below. At stations LN1 and LN9 (LN9 not shown), the uppermost spike is just below a rapid decrease in temperature, but this association is not as obvious at the other stations offshore of the Linthipe River. A surface turbid layer is not detected at the sites offshore of the Ruhuhu River (Fig. 3d).

A benthic turbid layer is typically detected at stations offshore of the Linthipe and Dwangwa rivers (LN1, 2, 3, 7, & 9; DW1, 2 & 3). These profiles reveal a maximum TSS concentration at the lake floor that is approximately 1.0 to 1.5 mg/L more turbid than the least turbid water at the respective site. The layer decreases in turbidity to baseline levels with height above the lake floor, and is 20 to 30 m thick. Except for four sites (LN8; RH4, 7, & 8), the stations with a water depth less than 200 m revealed a benthic turbid layer. In contrast, benthic turbid layers are not detected at any station with a water depth greater than 200 m (DW4; ML1, 2, 3, & 4; RH6, 9, 10, &11). The absence at the four sites can be explained by a deployment depth that was not within 20 m of the lake floor, so that the instrument package may have missed an existing nepheloid layer, but all of the casts at the deep-water stations were within 10 m of the lake floor including five casts that reached the lake floor (DW4; ML1, 2, 3; RH9).

All of the transmissometer casts that penetrated the monimolimnion (ML2, 3, & 4; RH6, 9, 10, & 11; DW4) reveal a small increase in turbidity of 0.1 to 0.2 mg/L at 180 to 200 m compared to adjacent depths (Figs. 3b-d). Variations in the depth, thickness, and intensity of the layer are small and lack consistent trends across the lake. The depth of the layer is below the thermocline and is at or just above the chemocline.

TSS profiles from offshore of the Ruhuhu Delta reveal a mid-depth turbid layer (Fig. 3d). The profile at site RH4, which is closest to the river mouth, suggests TSS values greater than 30 mg/L between a depth of 30 and 65 m. Even though these high TSS values are beyond the range of TSS values used to field calibrate the transmissometer, the relative trends in turbidity are reproducible and are discussed below. The layer is traceable from the river mouth to stations almost 5 km to the south (RH8 & 9) and almost 10 km to the west (RH10 & 11). The layer is not conspicuous in the profiles at the stations to the north (RH6 & 7). When present, the thickness and intensity of the layer decreases with distance from the mouth. The layer coincides with the thermocline and either coincides with or is a few meters below a fresh-water plume with conductivities (κ_{25}) as low as 213 μS/cm (Fig. 3d). Conductivities at other stations in the lake increase with water depth from about 258 μS/cm at the surface to 270 μS/cm at 680 m with fifty percent of the increase between 160 and 240 m (Fig. 3c: Halfman 1993). The vertical separation of turbid and less saline water in the water column is more pronounced with distance from the river mouth.

DISCUSSION

A hypothetical model, based on a survey of the literature sited above, outlines the potential sources and distribution patterns of suspended sediment in a tropical rift-lake (Fig. 4). It provides a useful reference for the following discussion on the background turbidity, and upper, intermediate and benthic turbid layers in Lake Malawi.

The background TSS concentrations detected in the open lake are between 0.15 and 0.35 mg/L and are slightly lower than values reported for the open water regions of Lakes Superior (0.2 to 0.7 mg/L: Capel and Eisenreich 1985, Baker and Eisenreich 1989, Halfman and Johnson 1989), Michigan (0.5 to 2 mg/L: Eadie and Robbins 1987), and Ontario (0.5 to 2 mg/L: Mudroch and Mudroch 1992). The background TSS concentrations are similar to mean phytoplankton biomass concentrations for Lake Malawi (0.15 mg/L: Degnbol and Mapila 1981, Hecky and Kling 1987). Higher biomass values are reported for the southern portion of the lake than elsewhere. This trend parallels higher average turbidity at the Linthipe Stations than those to the

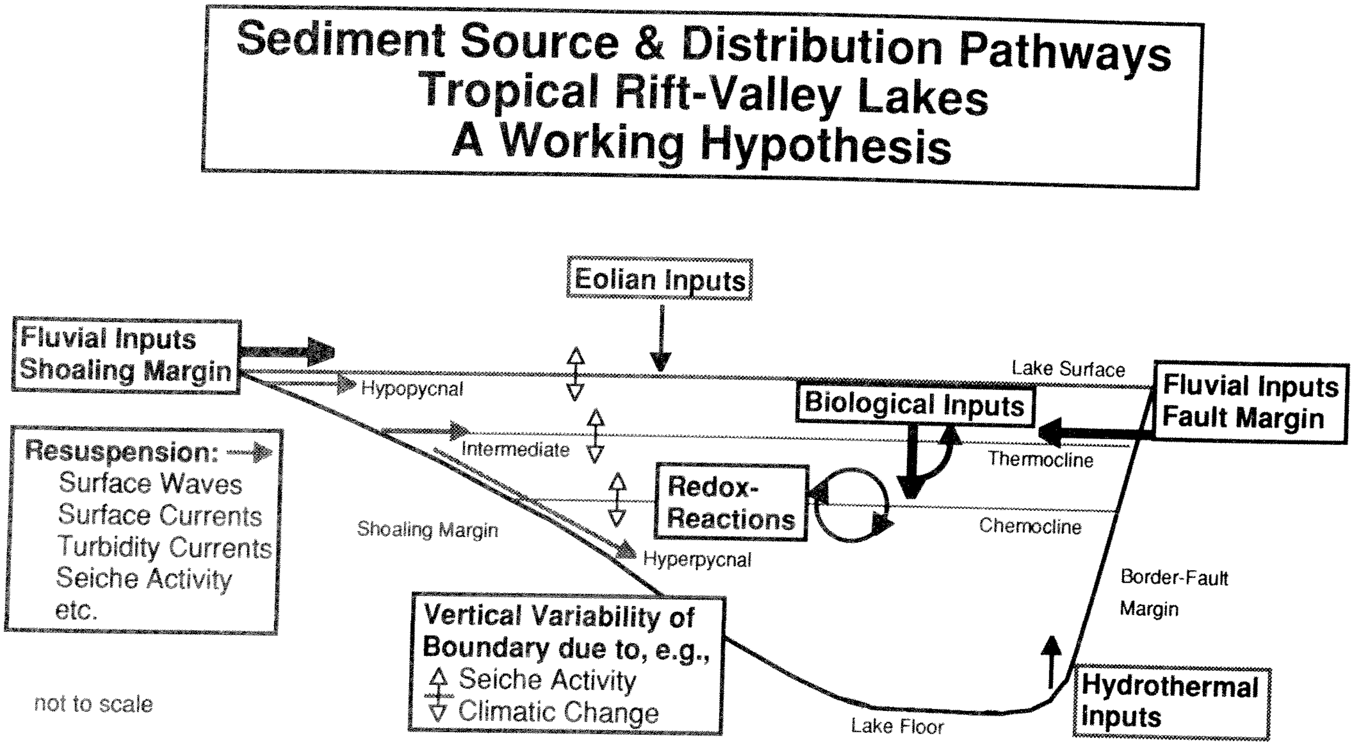


FIG. 4. Hypothetical model of suspended sediment source and distribution pathways in a tropical rift-lake.

north. These observations suggest that biological productivity contributes to the turbidity detected throughout the lake. Biological productivity impacts sedimentation in the lake. Mass accumulation rates of biogenic silica range from 1 to 10 mg/cm^2/yr and represent approximately 5 to 20% of the total sediment flux to the lake floor based on analyses of sediment cores (Johnson and Ng'ang'a 1990, Owen *et al.* 1990, Finney and Johnson 1991) and sediment trap studies (Haberyan 1990, Pilskaln and Johnson 1991).

The spatial configuration for the surface and near-surface layers is complex and suggests that a number of processes influence the distribution of suspended sediments at or near the surface of the lake. The layer may represent the accumulation of algae just above a sharp increase in water density associated with a step in the thermocline. Water density in the mixolimnion is primarily controlled by temperature. The association is consistent with greater turbidity and increased productivity at the southern end of the lake, but biomass concentrations are too low to account for the entire turbidity. The hypothesis also fails to adequately explain the numerous spikes in turbidity off the Linthipe River that are not associated with steps in the thermocline. The surface layer may also represent hypopycnal dispersal of either warmer river water or resuspension events of warmer nearshore water above cooler lake water. This hypothesis is consistent with surface turbid layer(s) detected at sites DW1, DW2, LN7, & LN8. A pond and large swamp located at the end of the Dwangwa River probably increase the temperature of the water discharged into the lake. Yet the turbid layers in the surface waters offshore of the Dwangwa and Linthipe rivers lack significant spatial trends consistent with hypopycnal dispersal. This inconsistency may reflect the lack of significant rainfall just before profiling the Linthipe and Dwangwa Deltas (central East Africa experienced a severe drought in 1992), the retention of suspended sediment by the pond and swamps at the mouth of the Dwangwa River, and/or the redistribution of suspended matter by wind induced currents from numerous directions.

Wind generated waves and surface currents interact with the upper turbid layer. We visually observed surface plumes of suspended matter in the southern arm of the lake that migrated laterally after changes in wind speed and direction. Upper and lower boundaries of the turbid layer usually coincide with steps in the thermocline. Finally, elevated turbidity at the nearshore sites compared to offshore sites, even at nearshore sites that are a few kilometers from fluvial inputs, suggests that surface-wave resuspension and surface-current redistribution of sediments is important.

The character of the benthic turbid layer is similar to but less intense than lake-floor nepheloid layers reported from the Laurentian Great Lakes. For example, an increase of approximately 2.0 mg/L was observed between the mid-layer particle-free water and the nepheloid layer in the western arm of Lake Superior (Halfman and Johnson 1989). Following the Laurentian literature, we suggest that the source of sediment to this layer may be the accumulation of material from above and/or the resuspension of sediment from the lake floor by large surface waves, surface currents, or seiche activity. Wind-induced waves and currents winnow the sediment to depths of over 100 m (Johnson and Ng'ang'a 1990), and the depth of the thermocline in Lake Malawi has been offset by over 50 m along a north-south transect in the lake during the windy season (Eccles 1974). Another important source of material for the benthic nepheloid layer may be turbidity currents; however, higher levels of turbidity were not observed within turbidity channels along the lake floor even though some stations were deliberately positioned within turbidity channels.

The turbid layer at or just above the chemocline may represent the accumulation of suspended matter from above, the growth of chemosynthetic bacteria, or the oxidation of dissolved iron and manganese and precipitation of the respective oxyhydroxides. A few turbid layers with similar TSS concentrations are observed between 50 and 200 m at a few sites (ML1 & 2; DW4; RH6 & 7). These layers may be due to sinking particles and suggests that the first option is plausible. Chemosynthetic bacteria commonly grow at the transition to anoxic waters in the Black Sea and other meromictic systems. Elevated abundances of nontronite (Fe-oxyhydroxide) are reported in the surface sediments at water depths of 80 to 160 m in Lake Malawi (Müller and Förstner 1973, Finney and Johnson 1991). Water samples are not available to conclusively support one or more of these possibilities.

The mid-depth turbid layer, detected offshore of the Ruhuhu River, is interpreted as an interflow plume from the Ruhuhu River. First, the concentration of TSS in the turbid layer decreases from the river mouth to sites farther west and south, and implies an obvious point source. Coriolis effect or other currents may have deflected the plume away from the stations to the north. Second, the plume coexists with unusually low water salinities (Figs. 3c & d). The river is less saline than the lake, and the basin experienced monsoon-style rainfall 2 days before the transmissometer casts. Settling of particles from the plume is a possible explanation for the increasing difference in depth between the fresh water and turbid layer with distance from the source. Third, side-scan sonar records typically reveal a blanket of fine-grained sediment over the delta fan, even in major turbidity channels which is not resolvable in 1-kHz, normal incidence seismic profiles (Johnson and Ng'ang'a 1990). The authors attribute the thin blanket to particles settling from above. Finally, station RH4 occupied a narrow, V-shaped, subaqueous valley at the mouth of the river (200 m wide × 80 m deep). The morphology enables the injection of turbid water below the surface of the lake.

A combination of factors may explain why an interflow plume is observed adjacent to the Ruhuhu River and not at the other deltas investigated in this survey. This delta was the only one surveyed after intense rainfall in the respective basin and underscores the relationship between local climatic conditions and the supply of suspended material. Cloudy skies, cooler air temperatures, higher relative humidity and an implied shorter residence time of water in the Ruhuhu catchment during this high-discharge event combine to introduce cooler water to the lake (compared to the other rivers). This is the only delta in this survey with a "shelf break" that is incised by a number of deep, V-shaped, subaqueous valleys. The sharp change in gradient due to the juxtaposition of the mouth of the Ruhuhu River with a basin boundary fault probably promotes excavation of deeply incised valleys into the delta complex, especially during low-lake stands. A seismic survey of the S. Rukuru Delta, a system that enters the lake at another basin boundary fault, also reveals numerous incised valleys (Scholz *et al.* 1993). The subaqueous valley at the Ruhuhu allows for the injection of turbid water below the surface of the lake. Thus, the plume effectively bypasses the redistributional influence of surface waves and currents that is important elsewhere in the lake.

The existence of the interflow broadens our knowledge of sedimentation in tropical rift basins. Previously, hyperpycnal flow, i.e., turbidity currents, was proposed as the major transport pathway for fluvial sediments. Seismic reflection profiles and sediment cores reveal evidence for turbidites and turbidity channels even in the deepest basin of the lake (Johnson and Ng'ang'a 1990, Scholz *et al.* 1990). In addition, time-series sediment trap data from a mooring located below the chemocline in the central portion of the north basin (about 50 km from nearest major river) accumulated a significant flux of autochthonous biogenic material, especially during the windy season, but the accumulation of clastic material was much less than expected, especially during the rainy season (Pilskaln and Johnson 1991). However, our data indicate that interflow mechanisms are important in the dispersal of fluvial sediments. Perhaps the sediment trap was too far away from fluvial sources to detect interflow material. The co-existence of turbidity and interflow dispersal mechanisms in a lake is not unique to Lake Malawi. Both mechanisms transport suspended particles from the Rhone River into Lake Geneva (Giovanoli 1990).

The significance of this interflow event is estimated by calculating the flux of material to the lake floor assuming all of this material is uniformly deposited over the Ruhuhu Fan. The calculation requires water discharge rates, surface area of the subaqueous fan, and sediment concentration at the source to the lake. The first two quantities are known; the average discharge of the Ruhuhu River is 40 m^3/s (Pike 1964, Scholz *et al.* 1993), and the delta fan is approximately 400 km^2 (Johnson and Ng'ang'a 1990). Both values are conservative estimates, e.g., the discharge of the Ruhuhu just after the 2-day rainstorm was probably larger than the average rate. The concentration of suspended material in the interflow at site RH4 is estimated in two ways. First, extrapolation of the TSS - attenuation calibration suggests that the TSS concentration in the mid-depth layer at site RH4 is over 30 mg/L. The lower limit for the plume's TSS concentration is conservatively set at 25 mg/L because it is the upper detection limit for the transmissometer. Second, an upper limit for the concentration is 1,500 mg/L. We assumed that the bulk density of the interflow layer is equal to the potential (depth adjusted) density of the water mass just below the thermocline, and a particle density of 2.5 g/cm^3. We then used the freshwater PVT equations of Chen and Millero (1986) and conductivity to salinity conversion of Hill *et al.* (1986) to calculate water density. This calculation provides a maximum density and maximum TSS concentration for the interflow layer because its density must be lower than the density of the underlying water mass to maintain the observed separation. Using this range of concentrations, the flux of material to the delta surface is between 0.02 to 1.0 $mg/cm^2/day$. The flux of sediments by this single event brackets the measured long-term sediment flux to the lake floor (0.05 - 0.1 mg/cm^2/day: Johnson and Ng'ang'a 1990, Owen *et al.* 1990, Finney and Johnson 1991).

CONCLUSIONS

Total suspended solid concentrations in Lake Malawi are typically between 0.1 and 0.5 mg/L. They are lower than those reported for the lower Laurentian Great Lakes. Fluvial inputs are an important source of suspended sediment to the basin. Structural components of the basin, i.e., shoaling or border-fault margin, and climatic factors both influence the amount and the dispersal pathway of the fluvial inputs. Elevated levels of turbidity at or near the surface, intermediate, and bottom segments of the water column suggest that hypopycnal, intermediate, and hyperpycnal pathways are active in the lake. Other important sources of suspended sediment probably include biological productivity at the surface, chemical or biological processes at the chemocline, and resuspension events by wind-induced waves and currents, and seiche activity.

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