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The Vertical Distribution of Runoff and its Suspended Load in Lake Malawi

Greg K. McCullough*, **David Barber, and Paul M. Cooley**

Centre for Earth Observations Science
Department of Environment and Geography
University of Manitoba
Winnipeg R3T 2N2

ABSTRACT. *Lake Malawi, in south-eastern Africa, is subject to increasing loading of suspended solids caused by land use pressure in its watershed. Whether this load is transported into the lake as overflow, interflow or deep underflow determines to a large extent its effect on the lake ecosystem. In this paper, vertical distributions of suspended solids in the Linthipe River delta region of the lake are described from multiple surveys during two rainy seasons. These data are supplemented by data from a single survey near four northern rivers also tributary to the lake. Profiles of temperature, conductance, and suspended solids concentrations (SSC, estimated from optical backscatter and beam transmission) are used to identify fluvial intrusions into the water column. Most inflow plunged to the seasonal metalimnion where it spread along high density gradients as interflow. While SSC in surface plumes rarely exceeded 10 g m^{-3}, and in intrusions in the lower metalimnion was rarely greater than 1 g m^{-3}, concentrations up to 420 g m^{-3} were recorded in interflow near the thermocline. Although storm runoff density often exceeded 100 m depth-equivalence in the lake, underflow density was reduced to metalimnion-equivalence (30–50 m depth) within a few 100s of meters of the river mouth. We attribute bottom-attached turbid layers, and the few unattached turbid layers in the lower metalimnion, all with positive conductance anomalies, to sediment resuspension and not to runoff. We conclude that the upper metalimnion is the prevailing pathway carrying watershed runoff horizontally throughout Lake Malawi.*

INDEX WORDS: *Delta processes, mixing, sediment transport, hyperpycnal flow, interflow, Lake Malawi.*

INTRODUCTION

The fishes of Lake Malawi (known as Lake Nyasa in Tanzania, and Lake Niassa in Mozambique) are a major source of protein for the people of Malawi and because of their beauty and diversity, a significant component of the tourist economy. Increasing nutrient and sediment yields associated with development in the watershed (Hecky *et al.* 2003) may have an adverse impact on this valuable resource. Several recent studies have documented reductions in benthic invertebrate abundance (Amin and Barton 2003), fish condition (Duponchelle *et al.* 2000) and species richness (Sululu 2000) associated with seasonal sediment discharge into Lake Malawi. Hecky *et al.* (2003) showed that 80–90% of major nutrients in stream flow into Lake Malawi is transported in the suspended load. Guildford *et al.* (1998) showed that increasing loading of phosphorous in particular may be expected to favor nitrogen fixing, filamentous cyanobacteria, including species toxic to both fish fauna and humans.

Some runoff into Lake Malawi sinks to the metalimnion (Halfman and Scholz 1993) and it has been argued that hyperpycnal flow may at times pass below the chemocline (Johnson *et al.* 1995, Kingdon *et al.* 1998, Vollmer *et al.* 2005). However, although underflow can persist to the bottom in stratified temperate-latitude lakes (*e.g.*, Lambert *et al.* 1976, Wüest *et al.* 1988), this has not been demonstrated for deep tropical lakes. The biological impact of increased inputs of suspended solids varies with the depth to which the load is delivered. Light attenuation, which would tend to reduce productivity, is maximized where sediment-laden runoff spreads buoyantly. Attenuation is negligible

*Corresponding author. E-mail: GregMcCullough@cc.umanitoba.ca

where runoff plunges below the euphotic zone, unless particulates in deep interflow layers are mixed back to the surface. In the short term, the latter case may be optimal for primary production, in that the dissolved nutrient load is returned to the euphotic zone even as light attenuation is reduced because some of the larger/more dense particulates will have settled out. In the longer term, dissolved nutrients carried to any depth in Lake Malawi are eventually returned to the surface by vertical mixing (Bootsma and Hecky 1993). In anoxic water, as below 250 m in Lake Malawi, particle-bound iron and with it, sorbed phosphorous are released into solution (Hecky *et al.* 1996). Consequently, hyperpycnal flow into the monimolimnion could actually increase the fraction of biologically available phosphorous and iron in the total load delivered by runoff, at least relative to any process that resulted in losses of suspended particulates by sedimentation above the chemocline.

In a companion paper in this issue, McCullough and Barber (2007) discuss the degree and spatial extent of light attenuation by turbid surface plumes developed in Lake Malawi near the mouth of the Linthipe River. In this paper, we use data from CTD (conductivity, temperature, and depth profiler, in this case with additional sensors allowing estimation of suspended solids concentration) surveys completed over the course of two rainy seasons to develop a statistical summary of vertical distributions of suspended solids in Lake Malawi near the mouth of the Linthipe River. We show how these distributions result from a particular history of river-lake density relationships over each rainy season. Using CTD casts recorded near the mouths of northern tributary rivers, we examine the applicability of our results to the whole lake. Finally, we argue that the metalimnion is the prevailing pathway carrying watershed runoff horizontally throughout Lake Malawi, and that deeper sinking of runoff must be an infrequent event at best.

STUDY REGION

Lake Malawi is the southernmost of the East African Rift Lakes. It is 560 km long, 40–70 km wide, and 22,490 km^2 in area, with a terrestrial watershed of 75,300 km^2 (Spigel and Coulter 1996) (Fig. 1). It is a stratified lake, with a seasonal thermocline that develops in late November or December at 20–50 m depth and that is progressively eroded in a windy season that begins in April or May, until the lake is mixed to 100–150 m depth by July or August (Patterson and Kanchinjika 1995). Water deeper than 200–250 m is perennially homothermal and anoxic (Gonfiantini *et al.* 1979, Vollmer *et al.* 2002) but not wholly isolated from upper layers. Estimates of exchange rates between the upper mixed layer and the monimolimnion range from 5–6% of its volume per year (Vollmer *et al.* 2002) up to 20% y^{-1} (Gonfiantini *et al.* 1979) and higher.

The site of this study is a semicircular region around the mouth of the Linthipe River in southern Lake Malawi (Fig. 1). The Linthipe River drains an 8,560 km^2 watershed and is the fourth largest tributary to Lake Malawi. Over 90% of its discharge occurs in the rainy season months of December–April (DOW 1986). At its mouth, it has formed a small Gilbert-type sand delta with a sub-aqueous distributary plain bounded by intermittently sub-aqueous/sub-aerial shoals and a steep foreset face. Hyperpycnal flow down the delta front is mostly constrained to south-eastward path by a subaqueous ridge underlying the Maleri Island chain (Fig. 1).

METHODS

Data for this study were collected during the 1998 and 1999 rainy seasons, mostly in the form of water column profiles along up to five transects radiating outward into Lake Malawi from near the mouth of the Linthipe River. We recorded 534 vertical water column profiles of pressure, temperature (T), conductivity (corrected to specific conductance at 20°C = K), and optical backscatter using a Richard Brancker Research (RBR) Limited XP-400 CTD. Another 114 profiles of pressure, T, K and beam transmission were recorded with a Sea-Bird Electronics Inc. SeaCat SBE 19-01 CTD. Linthipe River water was sampled and RBR CTD casts were recorded at a point in fast-flowing water near the center of the channel 200–300 m upstream of the lake. CTD data were averaged at 1 m intervals prior to further processing. River water samples were depth integrated to about 10 cm from the bottom, in a channel typically 0.5–1.5 m deep. All sensors on the RBR CTD were recalibrated by the manufacturer prior to each field season. Sensors on the SBE CTD were recalibrated by the manufacturer in 1996. The SBE CTD beam transmissometer was recalibrated in the field in December 1977 and March 1999. Station locations were determined using a Trimble® Scout Global Positioning Systems (GPS) unit. GPS data were not differentially corrected.