Management implications of the physical limnological studies of Rusinga Channel and Winam Gulf in Lake Victoria

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Abstract

During Apr.-May and Aug. 2005 intensive field investigations were undertaken to characterize the physical limnology of Winam Gulf and Rusinga Channel regions of Lake Victoria. Both the field data and numerical simulations with the three-dimensional (3D) hydrodynamics model, ELCOM (Estuary, Lake and Coastal Ocean Model), during these two field studies led to two major conclusions. First, though water currents in Rusinga Channel can be quite large (ca. 10-50 cm s^{-1}), exchange through the channel is low because the tidal-like oscillations result in low net transport over a 24 hour period. Second, Winam Gulf can be segmented into four regions, two of which have relatively low flushing rates as compared to time scales of biogeochemical processing. Regionally, on the basis of these physical limological findings the implications for water quality management strategies for Winam Gulf are presented. Internationally, the role of Winam Gulf as a net source or sink of nutrients and pollutants to the open waters of Lake Victoria is addressed.

Key words: Hydrodynamic Modeling, Water Quality Management, Winam Gulf

Introduction

Lake Victoria has undergone considerable ecosystemic changes over the past 50 years. Most of the haplochromine cichlids became extinct after the explosive increase of introduced Nile perch (*Lates niloticus*) in the 1980s (Kaufman 1992). The extent of anoxia in the deep portions of offshore waters has increased recently (Hecky 1993) in comparison with past conditions (Talling 1966). Phytoplankton biomass has increased in the Ugandan offshore waters (Muggide 1993, Hecky and Bugenyi 1992) and in the Kenyan inshore waters of Winam Gulf (Ochumba and Kibaara 1989). Further, the occurrence of blue-green algal blooms has become more frequent in Winam Gulf (Ochumba and Kibaara 1989). Three hypotheses are likely to be the causal mechanisms for the eutrophication of Lake Victoria over the past 45 years (Reinthal & Kling 1994). Firstly, the loss of the haplochromine cichlids has resulted in less grazing of the phytoplankton. Secondly, human population growth and land use change has led to increased nutrient loading and greater algal biomass. Lastly, climate change has caused a shallower mixed layer, increased persistence of seasonal stratification, and less ventilation of bottom waters.

The Kenyan portion of Lake Victoria encompasses the largest embayment of the lake, Winam Gulf, and has numerous sources of nutrient and pollutant loading. Recent debates regarding the contribution of Winam Gulf to the eutrophication of the main basin of Lake Victoria has not considered the exchange between the water bodies. In this paper, we build on recent physical limnological investigations of Rusinga Channel from a companion paper (Antenucci *et al.,* 2005) to assess the role of Winam Gulf on the overall eutrophication of Lake Victoria by addressing the exchange dynamics. Secondly, we consider the exchange amongst different regions of the Gulf, and evaluate the scope for catchment management to improve local water quality. Field data from recent surveys of Winam Gulf (Apr.-May and Aug. 2005), three-dimensional hydrodynamic simulations, and a brief literature review serve as the basis to consider possible management strategies to improve the Gulf's water quality.

Study site

The three riparian nations of Kenya, Uganda, and Tanzania have 6%, 45%, and 49% of Lake Victoria (3°S to 0.5°N, 31°40'E to 35°E) as territorial waters, respectively. The lake has a surface elevation at ca. 1134 m, mean surface area of 68,800 km^2, mean depth of 40 m, and maximum depth of ca. 70 m (Figure 1A). The catchment area is approximately 195,000 km^2, which also includes Rwanda and Burundi. Lake Victoria serves as an important water resource for domestic and industrial purposes, supports a valuable fishery, and is used for transportation for regional trade.

The Kenyan waters of Lake Victoria include Winam Gulf (also known as Kavirondo Gulf or Nyanza Gulf) and the northeastern corner of the main lake, a total area of ca. 4200 km^2 (Figure 1B). Winam Gulf has a surface area of ca. 1,800 km^2 and is connected to the open waters by Rusinga Channel. The Channel has a complicated bathymetry with numerous deep holes separated by sills. Several large rivers (Sondu and Nyondo) enter the Gulf in the southeast as major point sources of nutrients and sediments (Okungu & Opanga, 2004) as considerable agricultural and industrial activity occurs in these catchments generally associated with sugar cane (Scheren *et al*., 2000). Several large cities (Kisumu, Homa Bay) discharge domestic waste effluent into the Gulf, resulting in high loads of biological oxygen demand (Scheren *et al.*, 2000).

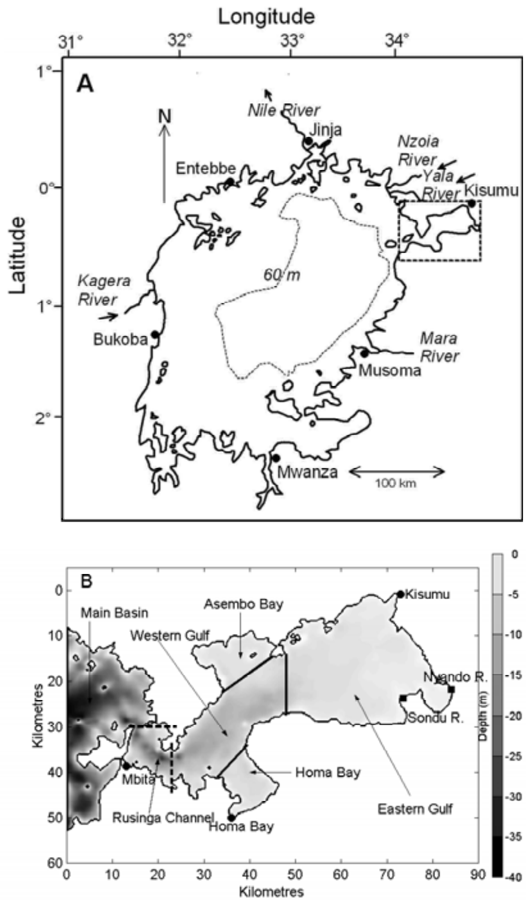


Figure 1. (A) Map showing the shoreline of Lake Victoria, the 60 m isobath, and major rivers and cities where the dashed box delineates the area of this study. (B) Map of the shoreline with shaded bathymetry, major cities (circles), major rivers (squares), hydrodynamic regions outlined by bold lines (Homa Bay, Asembo Bay, Eastern Gulf, Western Gulf), and dashed lines that define boundaries between the Western Gulf and the Channel, and the Channel with the Main Basin where exchange is estimated.

Methods

Therimstor chains were deployed in the offshore waters at T1 and Rusinga Channel at T2 during two field experiments (Apr. 22-May 4 and Aug. 5-16 2005). A full meteorological station (short and total radiation, air temperature, relative humidity, wind speed and direction) at T2 recorded measurements 2 m over the water surface with only wind speed and direction measured at T1. Water currents and directions, and surface level were measured with an acoustic doppler current profiler at T2. During the second field experiment (Aug. 5-16) additional surface level measurements were made at T1 and the Kisumu shoreline. A free-falling profiling instrument, the Finescale Profiler, was used to measure temperature, salinity, dissolved oxygen, pH and turbidity at 1 cm vertical resolution along transects of Rusinga Channel, Homa Bay and Winam Gulf (Gulf transects only during the 2nd study). The Fluoroprobe was attached to the Finescale Profiler and simultaneously recorded the biomass of various phytoplankton groups (diatoms, blue-greens, greens, cryptophytes). Refer to the companion paper by Antenucci *et al.* (2005) for more details on the instrumentation and locations of stations.

Three-dimensional hydrodynamic simulations with the Estuary, Lake, and Coastal Ocean Model, ELCOM (Hodges *et al.,* 2000), were carried out over both field studies to characterize transport in the Gulf and Channel. A uniform numerical grid was used with 250 m horizontal and 1 m vertical resolution (Figure 1B) and a model time step of 6 minutes. Free slip boundaries were used to model the sidewall (land) boundaries with a drag parameterization at the bottom boundaries. Meteorological forcing from T2 was applied over the entire domain except for wind speed, where T1 data was applied over the Main Basin. Water temperatures at the western open boundary were forced with T1 data. The open boundary surface levels were forced with T1 data during the second study, and T2 surface levels shifted back by 3 hours during the first study.

In order to estimate exchange and visualize transport, conservative tracers were employed in the ELCOM simulations. Transport in Rusinga Channel is similar to tidally-driven estuarine systems (Antenucci *et al.,* 2005). A common factor for defining the effectiveness of tidally induced harbor and lagoon flushing is the average per cycle, E, given by Nece and Richey (1975) as, $E=1-(C_i/C_0)^{1/i}$, where C_i is the concentration of a conservative substance after i tidal cycles and C_0 is the initial concentration of the same substance. Here, we defined i as the number of days, so that E was the percent flushing per day. We initialized two tracers over the Gulf and Channel to calculate flushing (dashed lines in Figure 1B) and three tracers to visualize flushing of several regions within the Gulf (bold lines in Figure 1B).

Results

During Aug. 2005 the study region of Winam Gulf, Rusinga Channel, and the northeastern offshore waters of Lake Victoria had gradients in physico-chemical and phytoplankton measurements (Figure 2). The salinity of Winam Gulf was about twice that of the offshore waters because of evaporative concentration during both the wet (Apr.-May, not shown) and dry (Figure 2) seasons. A similar spatial signature was evident in turbidity during both seasons with higher levels in the Gulf. High blue-green biomass occurred in the Eastern Gulf with surface accumulations of *Microcystis* observed during Aug. 2005 (J. Imberger, pers. obs.), presumably because buoyancy regulation by these algae provides a competitive advantage to overcome light limitation. In contrast, diatom levels were elevated primarily in Rusinga Channel where turbidity was lower and bio-available phosphorus from the offshore waters (Gikuma-Njuru and Hecky, 2005) was in closer proximity.

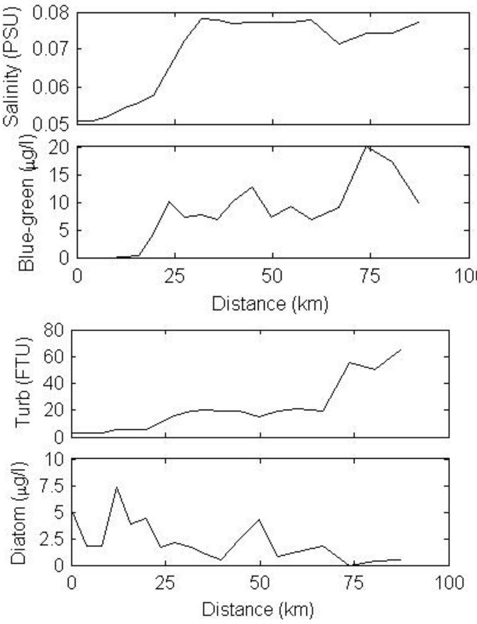


Figure 2. Transect from the Main Lake (0 km) to Kisumu (85 km) of averages over the upper 8 m of the water column of salinity (upper left panel), turbidity (upper right panel), blue-greens (lower left panel), and diatoms (lower right panel) during Aug. 14-16 2005. See Antennuci *et al.* (2005) for station locations

Temperature and current dynamics at T2 have been discussed in the companion paper (Antenucci *et al.* 2005). Here we briefly compare the observations at T2 with the simulation output of Apr.-May 2005. ELCOM modeled the temperature (Figure 3) and currents (Figure 4) well at T2. Diurnal stratification during the first half of the simulation was captured over the upper several meters of the water column, though it persisted longer into the evening than field measurements. The abrupt cooling of the water column mid-way through the simulation was captured by ELCOM, as was diurnal stratification in the upper several meters on Apr. 30, May 1 and May 3. Peak current speeds were generally captured by the simulation in phase with observations and generally of the same velocity. Similarly, current directions were captured well by ELCOM in terms of phase and duration. Favorable comparisons of the temperature and currents at T2 provide confidence in ELCOM simulations of other regions.

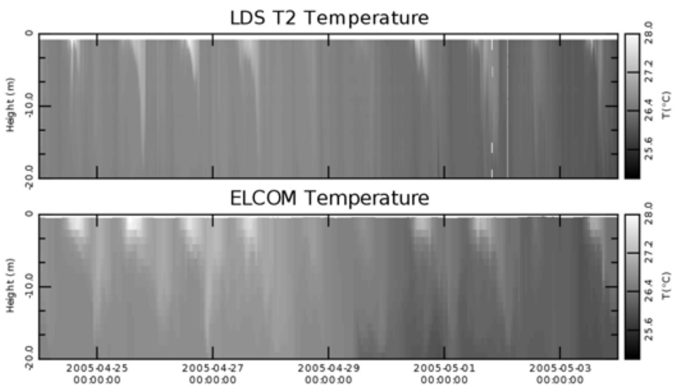
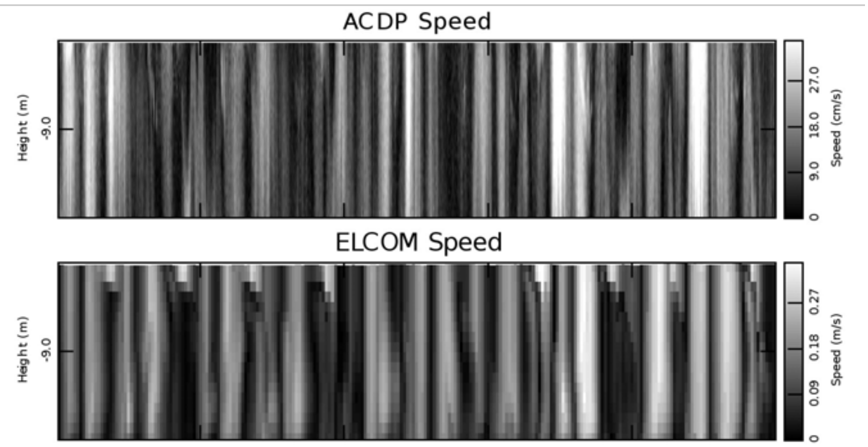


Figure 3. Comparison of observed (upper panel) and modeled (lower panel) temperatures at station T2 from Apr. 24-May 3 2005.



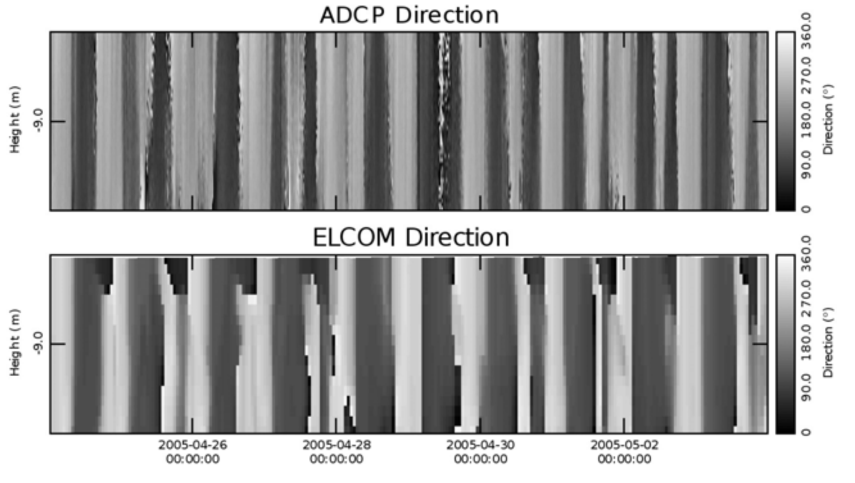


Figure 4. Comparison of observed current speeds (upper panel) and directions (lower middle panel) with modeled current speeds (upper middle panel) and directions (lower panel) at station T2 from Apr. 24-May 3 2005.

Conservative tracers in Asembo Bay, Homa Bay, and the eastern half of Winam Gulf indicate a range of exchange intensity (Figure 5). Over the 10 days the Eastern Gulf was relatively uncoupled from the Western Gulf. The major feature was the development and persistence of a clockwise topographic gyre over the Eastern Gulf, with features similar to patterns from LANDSAT images. In contrast, the tracer in Asembo Bay had a short residence time because of greater flushing with the Western Gulf. Flushing in Homa Bay was intermediate between Asembo Bay and the Eastern Gulf. The city of Homa Bay in the southwestern corner of Homa Bay is located in a region with relatively low flushing rates.

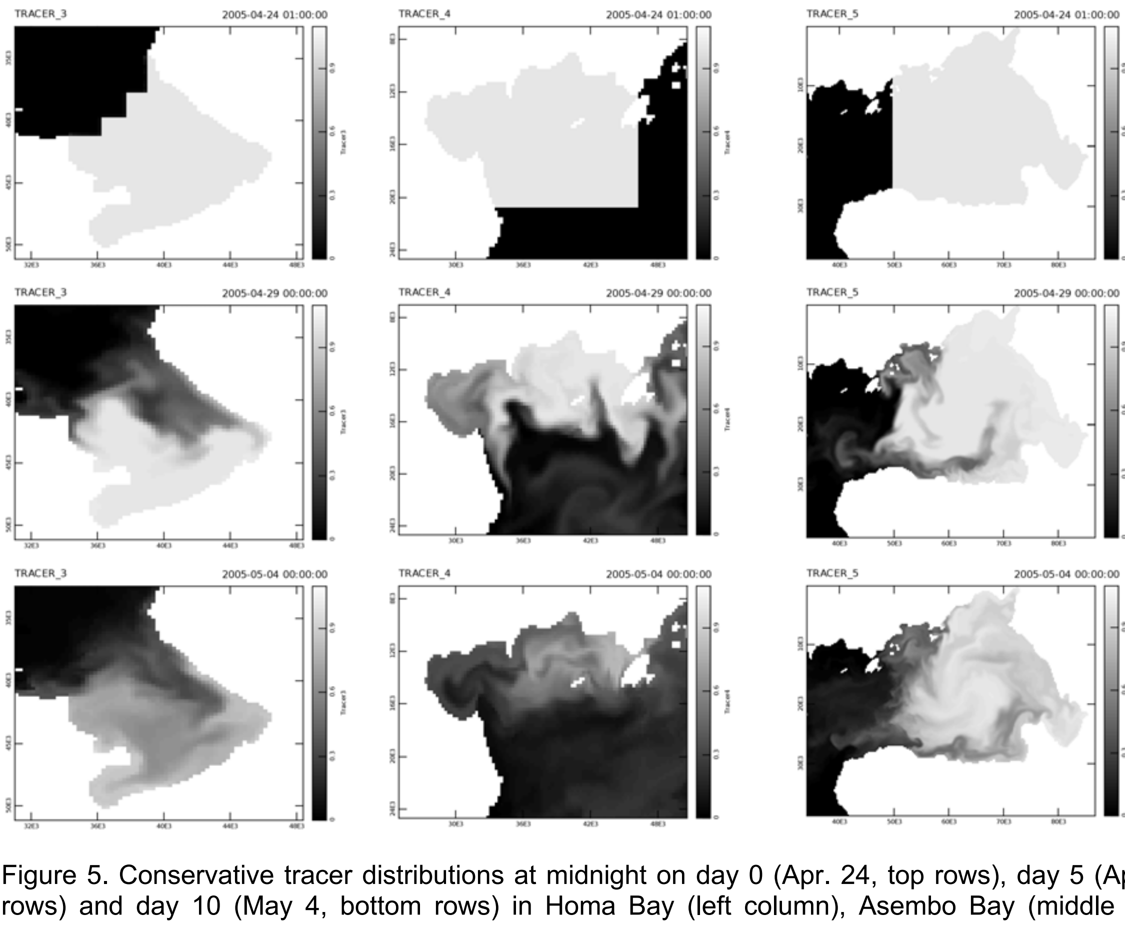


Figure 5. Conservative tracer distributions at midnight on day 0 (Apr. 24, top rows), day 5 (Apr. 29, middle rows) and day 10 (May 4, bottom rows) in Homa Bay (left column), Asembo Bay (middle column), and eastern Winam Gulf (right column).

Exchange estimates were made with ELCOM simulations across the two vertical planes at the Gulf-Channel and Channel-Open Water interfaces (dashed lines in Figure 1). The first field experiment occurred during the wet season and the lake level rose ca. 10 cm. The flushing estimates were between 0.2-0.3% per day over the two periods, which yielded a flushing time of ca. 300-500 days.

Discussion

Even though observed and simulated currents in Rusinga Channel are often in excess of 20 cm s^{-1} (range 0-50 cm s^{-1}, Figure 3), the net exchange between Winam Gulf and the offshore waters is low. These currents are primarily generated by tidal-like variations in surface levels (i.e. barotropic forcing) with 6-12 hour periods (Antenucci *et al.* 2005). Hence, even though the transport distance of the Channel water masses can be in excess of 3-5 km during an 'incoming tide', a similar length scale of movement occurs during the 'outgoing tide', which results in relatively low net transport.

The flushing time scale of Winam Gulf is on the order of 1-1.5 years over the conditions of our two field campaigns. This provides ample duration for fate processes to buffer the effects of external inputs from point sources (rivers and cities) and diffuse shoreline sources. Our current modeling investigations are aimed to improve understanding of the fate of nutrient loading from these point sources.

Unfortunately, our sampling did not coincide with periods of high inflows, which may result in considerably higher flushing and short-circuiting of riverine loads more directly to the Main Lake. A recent high flow event from 2003 with average discharges of 180 m^3 s^{-1} for the Sondu River and 400 m^3 s^{-1} for the Nyondo River was simulated to ascertain short-circuiting. The tracer of the flood inflows was confined primarily to the Eastern Gulf by the topographic gyre (not shown). These results highlight that even during high discharge periods, the region that is most affected by poor water quality from the rivers is the Eastern Gulf.

The tracer simulations (Figure 5) indicate that there may be some scope for catchment and point source management to improve local water quality in the Eastern Gulf and Homa Bay. Catchment management practices to reduce nutrient, pollutant and sediment loading will likely improve the mean water quality of the Eastern Gulf after such flood events. Recent estimates indicate nearly 50% of the BOD load into Winam Gulf is from Kisumu, hence upgrades to wastewater treatment facilities would greatly improve local water quality (Scheren *et al.* 2000). Similarly, the water quality in the region of the city of Homa Bay would also benefit from improved wastewater treatment given the low flushing in the southeast corner of the bay (Figure 5) at the location of this urban center.

Recent bio-available phosphorus surveys consistently record higher levels in the nearby offshore waters than in the Gulf, which has been attributed to adsorption onto the inorganic particles in the turbid Eastern Gulf (Gikuma-Njuru & Hecky 2005). Nutrient sampling during our two field campaigns also revealed these patterns (Gikuma-Njuru, unpubl. data). Similarly, the inshore waters of Uganda near the Nile outflow are comprised mainly of particulate organic phosphorus with low levels of bio-available phosphorus, which suggests nearly all of the phosphorus is converted to organic forms in these inshore regions (Lehman & Branstrator 1994). We hypothesize that the adsorption and biological uptake of bio-available phosphorus in the eastern Gulf occurs because of high levels of turbidity and blue-green biomass (Figure 2). Additionally, the high biomass of cryptophytes (not shown) and diatoms profiled in Rusinga Channel during both field studies (Figure 2, J. Imberger & J. Romero, unpubl. data) suggests that sufficient bio-available phosphorus is transported either from the offshore waters or the particulate bound component from the Gulf becomes bio-available. There is no doubt that bio-available phosphorus concentrations have increased offshore recently (Hecky 1993) relative to the 1960s (Talling 1966).

In short, the role of Winam Gulf as a source or a sink of phosphorus remains uncertain. Currently, we are using ELCOM coupled to the ecological model, CAEDYM (Romero & Imberger 2003), to improve understanding of the fate and transport of particle-bound phosphorus from the Gulf and bio-available phosphorus from the Main Lake. These simulations will provide the first estimates of the fate and transport of nutrients and sediments throughout Winam Gulf and Rusinga Channel so that further refinements can be made to research priorities and to management options of the region.

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