Characterization of the Ugandan inshore waters of Lake Victoria based on temperature-conductivity diagrams

Andrés Cózar,[1] Luca Bracchini, Arduino Dattilo, and Steven Loiselle
Dipartimento di Scienze Chimiche e dei Biosistemi, Università di Siena, Siena, Italy

Nicholas Azza
Directorate of Water Development, Entebbe, Uganda

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[1] Temperature-conductivity diagrams are shown as a valid instrument to analyze the hydrographic structure of freshwater ecosystems, even along the surface waters. We put this method in practice in the Ugandan inshore waters of Lake Victoria. A complementary parameter (*T-C* anomaly) was used to differentiate between upland water intrusions. The relative value of the *T-C* anomaly provided information about the nature of the water intrusions and showed a considerable correlation with the biological characteristics of the water masses. The results indicated that the connections between catchment attributes, water characteristics, and biological community are quite direct in the inshore waters of Lake Victoria. *INDEX TERMS:* 1845 Hydrology: Limnology; 1890 Hydrology: Wetlands; 1803 Hydrology: Anthropogenic effects; *KEYWORDS:* conductance, Lake Victoria, phytoplankton, temperature, Ugandan inshore waters, wetlands

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1. Introduction

[2] Lake Victoria is the second largest lake in the world, covering 68,000 km^2. Lake waters are shared by three countries, Uganda, Tanzania and Kenya. Lake Victoria represents a unique reservoir of tropical biodiversity [e.g., *Sturmbauer and Meyer*, 1992] as well as a fundamental source of both nutrition and revenue for the East African population [e.g., *Ogutu-Ohwayo et al.*, 1997]. The lake catchment area supports one of the fastest growing populations in the world, between 3 and 4% per annum. Such growth is accompanied by increasing urbanization and intensive farming, which have led to significant changes in the watershed. Nutrient and pollutants loadings into the lake have increased by soil mobilization and sewage discharges [*Hecky*, 1993]. The lake has been undergoing a significant eutrophication process, which is compromising the Lake Victoria functions.

[3] The factors controlling the trophic evolution of the lake intensely interact in the inshore waters [*Lung'ayia et al.*, 2001]. Changes in the watershed have their most direct influence on the inshore area; on the other hand, the littoral population is closely linked to the inshore waters resources. The characterization of the hydrographic structure of the land-water ecotone is a basic task in the analysis of the functioning of a lake.

[4] In oceanography, the temperature-salinity diagrams (TS diagrams) are commonly used to differentiate between waters masses along the water column [*Pond and Pickard*, 1983]. In limnology, the use of such a method to classify water masses is more problematic due to the occurrence of some particularities. Firstly, the horizontal spatial component of the shallow inland waters is more relevant than its vertical component. The spatial heterogeneity of lakes, especially inshore areas, is more appropriately studied by using horizontal trawling rather than by vertical profiling. Below the surface layer, temperature and salinity can only be changed by mixing and advection. However, TS diagrams derived from surface trawling show the difficulty that water mass properties may also change due to heat and mass fluxes across the surface. Furthermore, the variability of the salinity in the freshwater ecosystems is higher than in the seawater. The objective of the present work is to assess the usefulness of the TS diagrams as tracer of water masses in Lake Victoria inshore waters. This tool could provide a way to explore the large shoreline of this lake (3,440 km). Our study area was located in the central part of the Ugandan coast (Figure 1). This coastline portion (400 km) integrates a wide diversity of potential point sources of water intrusions, including urban and industrial runoff, lake tributaries (Katonga River) and wetlands ecotones.

2. Material and Methods

[5] A continuous sampling method was constructed using a trawling water sampler. A coastline transect was performed over a 3 day period (7, 8 and 11 June 2003) along a route of 180 km. All transect surveys were approximately performed from 10:00 until 17:00. During these samplings, southerly winds mainly blew and rainfall was absent. The 7 June transect covered the southern part of the studied coast, and the 8 June transect the northern coast. The 11 June transect was focused in the internal zone of different

[1]Now at Área de Ecología, Facultad de Ciencias del Mar, Universidad de Cádiz, Cádiz, Spain.

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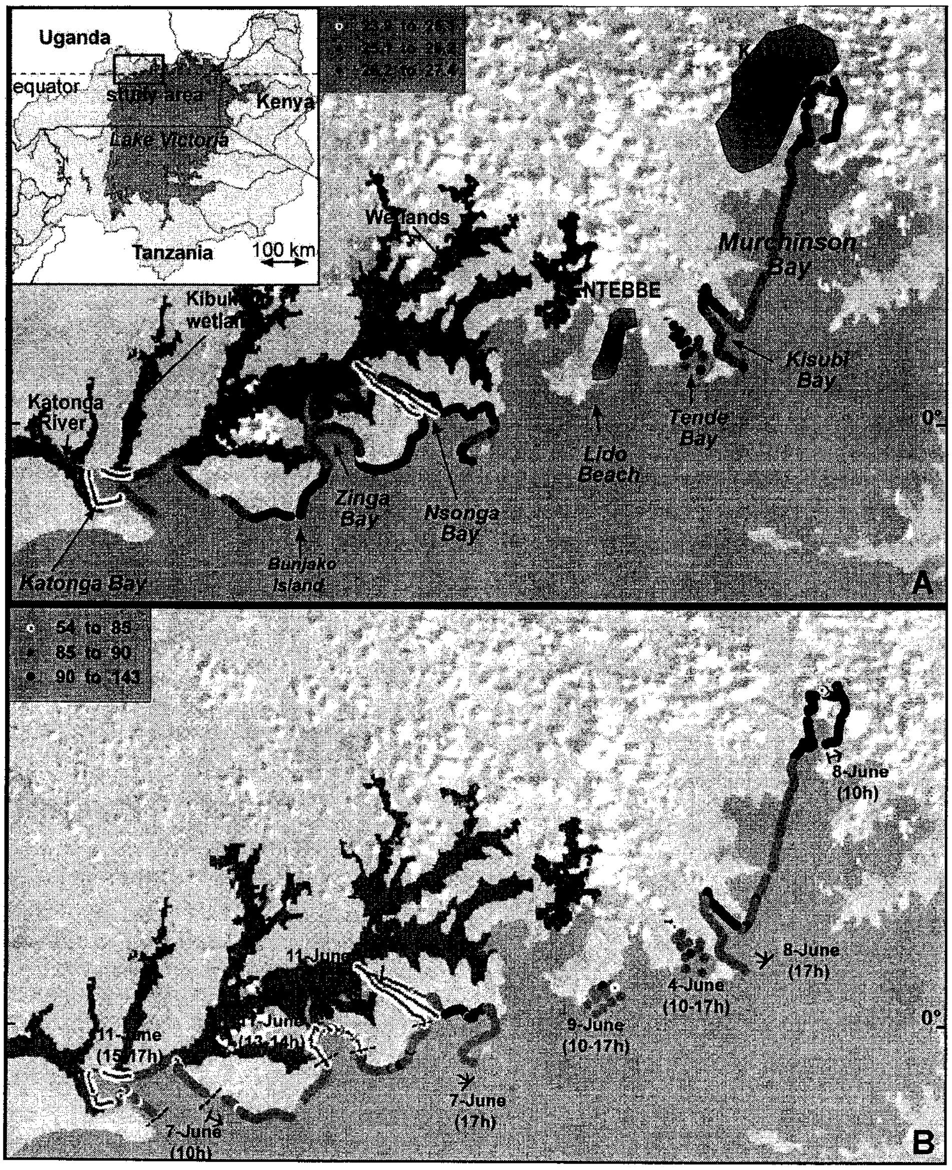

Figure 1. Catchment area of Lake Victoria (upper right corner) and the studied shoreline portion. The main wetland areas (dark gray) were determined through analysis of the near-infrared reflectances using reference points into a georeferenced satellite image (ETM sensor, Landsat-7, November 2001). The location of the largest population centers (Kampala, 1,210,000 hab.; Entebbe, 60,000 hab.) and the Katonga River are also indicated in the upper panel. (a) Trawling data of water temperature (°C). (b) Trawling data of specific conductance (μS/cm). The name of the sampled bays is indicated in Figure 1a, and the transect start (10:00) and end (17:00) times in Figure 1b (see section 2). The maximum diurnal water temperature time is usually registered above 14:00 [*MacIntyre et al.*, 2002].

embayments (Katonga, Zinga and Nsonga Bay). In Nsonga Bay, the outer half was covered during the 7 June transect, traveling along the southwestern and northeastern coasts. The 11 June transect covered the whole embayment. The boat firstly traveled (toward the inner bay) along the central part of the bay and then, traveled (toward the open lake) along the southwestern coast of Nsonga Bay. Thus the outer southwestern coast of this bay was covered during both sampling days (Figure 1).

[6] The boat traveled at a speed of 250 m/min to attain a water flux of 8.6 L/min. Water was continuously sampled from a depth of approximately 0.15 m and flowed into a 5 L black box. A Hydrolab multiprobe equipment was put into the black box and set to record water temperature (accuracy ±0.1°C) and specific conductance (accuracy ±2.0 μS/cm) every second. The conductivimeter was calibrated every day using a standard solution (Sigma Chemical). Specific conductance is the conductivity normalized to temperature of 25°C. This measurement is directly proportional to the salinity. However, the relation between specific conductivity and salinity depends on the composition of salt molecules. Thus the use of specific conductance instead salinity to build the TS diagrams facilitate the use of this method for inland water bodies. A Turner Designs fluorometer

(SCUFA) was also placed in the black box and set to record fluorescence every second. The fluorometer (wavelength excitation = 485 nm, measured wavelength = 680 nm) was calibrated every day with help of a secondary standard (Turner Designs). Chlorophyll-*a* concentrations were estimated from fluorescence measurements through a calibration curve determined using measurements of chlorophyll-*a* concentration from different lakes including Lake Victoria [*Talling and Driver*, 1963]. Despite the different sources of variability of the fluorescence signal (e.g., quenching, temperature), the chlorophyll-*a* concentrations and fluorescence showed a good linear correlation ($n = 43$, $R^2 = 0.9649$, $P < 0.01$). We will refer to the chlorophyll-*a* concentration derived from this method as estimated chlorophyll-*a* (*chl**). The geographical location during the trawling was recorded every minute using a GPS (Garmin GPS III). Simultaneous data of temperature (T), specific conductance (C) and *chl** were averaged every minute (60 measurements) and synchronized with the GPS record.

[7] Depth profiles of temperature and specific conductance were also performed every 10 km during the trawling. The extensive wetland areas that line much of Lake Victoria have been suggested as important buffer areas of the water runoff from the catchment [*Kansiimie and van Bruggen*, 2001]. Therefore high-resolution (1 km) grids of depth profiles were also performed to explore the mesostructure of inshore areas with different extensions of littoral wetland: areas with large wetland (Nsonga Bay, 24 profiles, 5 June 2003), with little wetland (Tende Bay, 15 profiles, 4 June 2003) and without wetland (Lido Beach, 17 profiles, 9 June 2003).

[8] A major benefit of the TC diagrams is the possibility to study the isopycnal surfaces because of the dependence of the density on both temperature and salinity. Water density was estimated according to *MacIntyre et al.* [2002].

3. Results

[9] The trawling approach allowed a rapid characterization of a large portion of the Lake Victoria shoreline. Temperature and specific conductance measurements showed a clear spatial pattern despite the expected diurnal variability (Figure 1). The inner area of the bays linked to large wetlands showed colder surface waters than the outer bay. Zinga Bay showed temperatures lower than 25.5°C while Katonga and Nsonga Bays reached temperatures below 25.0°C. Warmer temperatures were registered along the open shoreline and in the inner bays linked to relatively small wetlands (Tende, Kisubi and Murchinson Bays). The presence of large extensive wetlands was found to be the main factor to influence the thermal distribution, rather than the coastline morphology or the water depth. Water exchange between the wetland areas and the embayments may lead to cooler waters in the areas near the main wetland edges due to shading by floating mats of vegetation and organic matter. Specific conductance showed similar patterns to the temperature. Low specific conductance was observed in the bays linked to large wetlands (Katonga, Zinga and Nsonga Bays). High conductance was measured in Tende Bay, Inner Murchinson Bay and some areas of the open shoreline.

[10] The advection by wind may be also a relevant factor in the spatial distribution of water properties. For instance, southerly wind was consistent explaining the differences of coast-to-coast temperatures in Nsonga Bay. Wind was very effective at transporting warm surface layer water to the downwind end of the bay, but the windward shore of the bay was sheltered from such an effect.

[11] The analysis of the TC diagram showed well-differentiated patterns. When all the data are considered, a clear linear positive correlation between T and C for most of data was shown (Figure 2). Several clusters of data points strayed from this general pattern. When these outliers were examined, they were found to correspond to continuous transects (>6.5 km) performed in three embayments (Zinga Bay, Nsonga Bay and Inner Murchinson Bay). If these three data series are removed, a consistent linear regression model is formed: C (μS/cm) = $a + bT$ (°C), where $a = 11.7$ and $b = 2.9$ ($n = 460$, $R = 0.743$, $P < 0.01$). Note that the removed outliers fall out of the 99% predictive limits of the adjusted model. Bays with large wetland areas (Nsonga and Zinga Bay) were located under the 99% predictive limits. The points above these predictive limits were those of Inner Murchinson Bay. Data collected in Katonga Bay fell along the general TC line even though this bay showed the lowest surface temperatures.

4. Discussion

[12] The TC diagrams show the water masses as TC points. However, temperature and specific conductance are not conservative properties in the surface waters due to the fact that this layer remains in permanent contact with the atmosphere. Heat and matter fluxes across the lake surface change water temperature and specific conductance, respectively. Water temperature depends on the sum of surface heat fluxes components, including sensible heat, latent heat and radiation. On the other hand, specific conductivity is modified as a result of the evaporative and rainfall conditions at the lake surface. Therefore TC points in the superficial waters masses may drift in the TC diagram depending on the meteorological conditions, giving rise to the formation of new water masses.

[13] Distributions of surface salinity in the oceans are derived from the difference between evaporation and rainfall, which may cause latitudinal differences in the surface water balance on the order of 10–15 cm/month [*Pond and Pickard*, 1983; *Levitus et al.*, 1994]. In freshwater ecosystems, and especially in Lake Victoria, evaporation plays by far the major role controlling the salinity variations in freshwater ecosystems. Lake Victoria maintains an elevated evaporation and a very low salinity, reducing the effect of rainfall on the lake surface salinity when compared to ocean waters. The evaporation rate depends on multiple parameters, including wind speed, air humidity, atmospheric pressure, air and water temperature. Nevertheless, spatial differences in the evaporation rate in the study area are mainly due to differences in water temperature. Within the studied temperature range, the evaporation rate increases linearly with the water temperature (Figure 2). Temperature-derived differences in evaporation rate could induce differences in the water balance of the study area on the order of 10–15 cm/month. Spatial differences in the surface water balance in the deep ocean explain differences in salinity on the order of 2 psu, which corresponds to a variability of the salinity value of 5–10%. Therefore temperature-derived

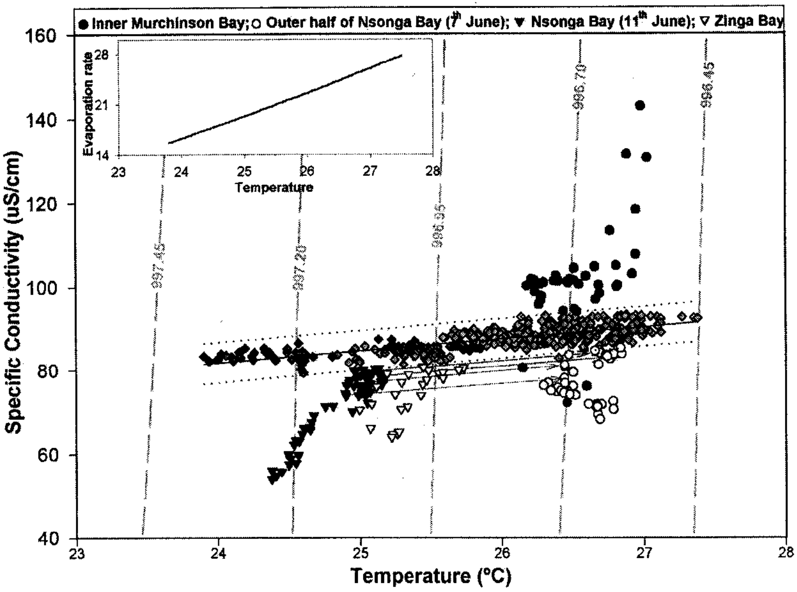

Figure 2. TC diagram obtained during the trawling along the Ugandan coast in June 2003. Dashed lines show the isopycnals in kg m^{-3}. The regression line (solid line) was determined using the rhombus points. Dark gray rhombuses correspond to Katonga Bay and light gray rhombus to the open shoreline. Dotted lines indicate the 99% predictive limits of the adjusted model. Data clusters from Murchinson, Nsonga, and Zinga Bays were not included in the regression analysis. The gray arrows indicate the drift of the TC points corresponding to areas of Nsonga Bay sampled both on 7 and 11 June (see section 2). This area (outer southwestern coast) showed similar A_{TC} values despite the different conditions of T and C. These results showed that combined use of T and C through A_{TC} was not significantly affected by the temporal variability of the water characteristics as the TC points drifted in parallel with the TC line. The inset shows evaporation rate (cm/month) versus water temperature (°C). The evaporation rates were estimated according to *MacIntyre et al.* [2002] and using average data of atmospheric pressure, wind speed, air temperature, and air humidity from Tindall Climatic Data Center. Therefore they are only approximations (see section 4).

differences in evaporation rate could explain the spatial variability in salinity found along the study area, which is of the same order of magnitude. The lineal *T-C* linkage (covariation) found in the open lake would result from the dependence of evaporation rate on water temperature. We will refer to the water masses drifting along the TC line as open lake water masses (OLW).

[14] In the inshore area, the catchments runoff plays also an important role in controlling the surface temperature and salinity. The main outliers identified in the TC diagram were coincident with potential point sources of water intrusions. Near the wetland ecotones or the urban coasts, TC points reached the highest differences with the modeled OLW TC line. Mixing between different water masses connects the corresponding points in the TC diagram, allowing the water masses to be identified within lines rather than points.

[15] The characterization and identification of catchments runoff intrusions is a fundamental task in understanding the human impact on lakes. Knowing the general linear function that OLW follow in the TC diagram, it is possible to quantify the deviation of the upland water intrusions from the OLW characteristics using the following equation:

$$A_{TC} = \frac{C_0 - b \cdot T_0 - a}{\sqrt{b^2 + 1}} = \frac{C_0 - 2.9 \cdot T_0 - 11.7}{3.1},$$

where A_{TC} indicates the distance of the point (T_0, C_0) from the above mentioned line: C (μS/cm) $= a + bT$ (°C) (Figure 2). Points under the TC line show negative distances and points above the line show positive distances. In the sense that A_{TC} represents the distance from the general *T-C* pattern, we will refer to it as a *T-C* anomaly. This distance can be used as a specific index to characterize irregular water masses and their intrusion into the lake. Results showed how the mixing of these upland water intrusions with OLW brings the TC points of the intrusion toward the OLW line.

[16] The *T-C* anomaly along all transects determined three main types of inshore waters, with negative anomalies, with anomalies around zero and with positive anomalies (Figure 3).

[17] 1. Negative anomalies were associated with bay waters linked to large littoral wetlands. The wetland's capacity to retain nutrients and diminish the conductance of the incoming waters [e.g., *Kansiimie and van Bruggen*, 2001] would explain the presence of water masses of different nature in Zinga and Nsonga Bays (with large wetlands). In the inner bay (near wetland), A_{TC} reached values below −5.

[18] 2. Other bays with little or no wetlands, such as Tende and Kisubi Bays, show anomalies around zero, generally between −0.5 and +0.5. Anomalies were also

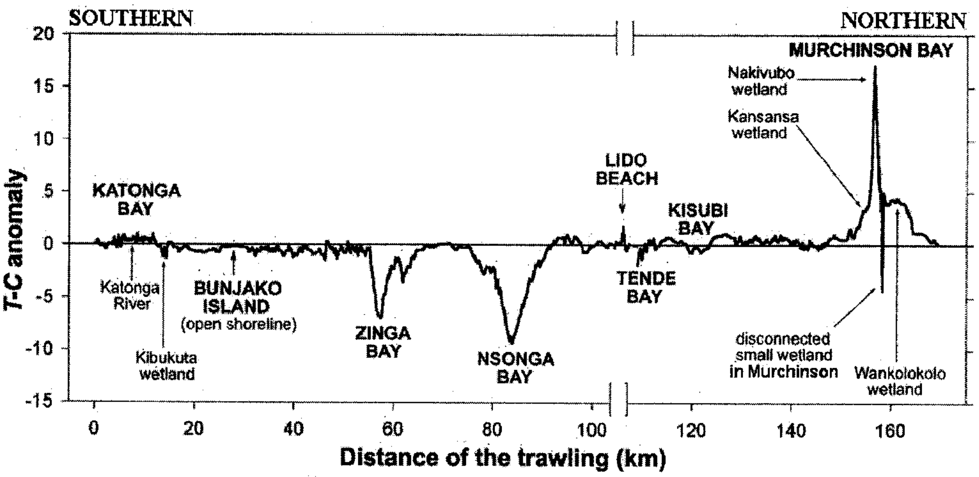

Figure 3. Data of *T-C* anomaly along the transect from Katonga Bay (southern Uganda) to Murchinson Bay (central Uganda). The transect identifies the main upland water intrusions along the Ugandan coast. The sensitivity of A_{TC} to water quality changes also allowed the mesoscale determination of secondary water intrusions. Sudden variations of A_{TC} distinguished small littoral areas associated with wetlands. The drainage of Kibukuta wetland into Katonga Bay or the drainage of a little undisturbed wetland (disconnected from urban watershed) into the highly impacted Inner Murchinson Bay are characterized by rapid changes in the A_{TC} value.

very close to zero in the open shoreline, especially in the land spit of Bunjako Island.

[19] 3. Positive anomalies above +0.5 were observed in Murchinson Bay and some small areas of the northern part of the studied shoreline. Anomalies were especially high (>+5) in Inner Murchinson Bay, which receives directly water discharges from Kampala city.

[20] Katonga Bay (with large wetland) showed a different pattern (slightly positive anomalies) compared with the other bays with large wetlands. Zinga and Nsonga Bays are fed by winding streams surrounded by wetland vegetation. Katonga Bay, however, is fed by a relatively large river that drains a large catchment (55% of the total Ugandan Lake Victoria catchment). The watershed includes extensive farming and numerous small human settlements. The large wetland that separates Katonga River from the lake appears to remove a large quantity of dissolved substances. However, the high flow rate through the Katonga wetland

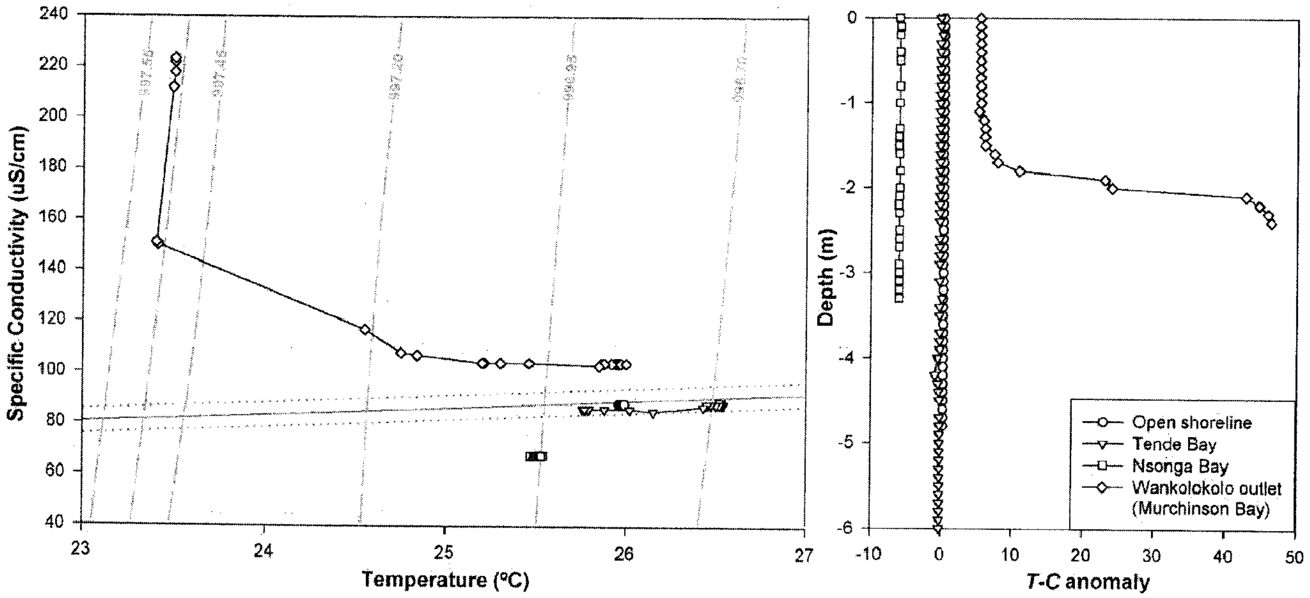

Figure 4. (left) TC diagram of different vertical profiles. (right) Corresponding A_{TC} profiles. Presented are one profile in the open shoreline, one in a bay with small wetland (Tende Bay), one in a bay with large wetland (Nsonga Bay), and another one in a disturbed wetland (Wankokolo outlet). The stability of the water column generally resulted from the lower temperature of the deep layers. The higher ionic concentrations in Murchinson Bay, however, allow for a small thermal inversion along the water column. Every selected profile in embayment was about 1 km from the wetland outlets.

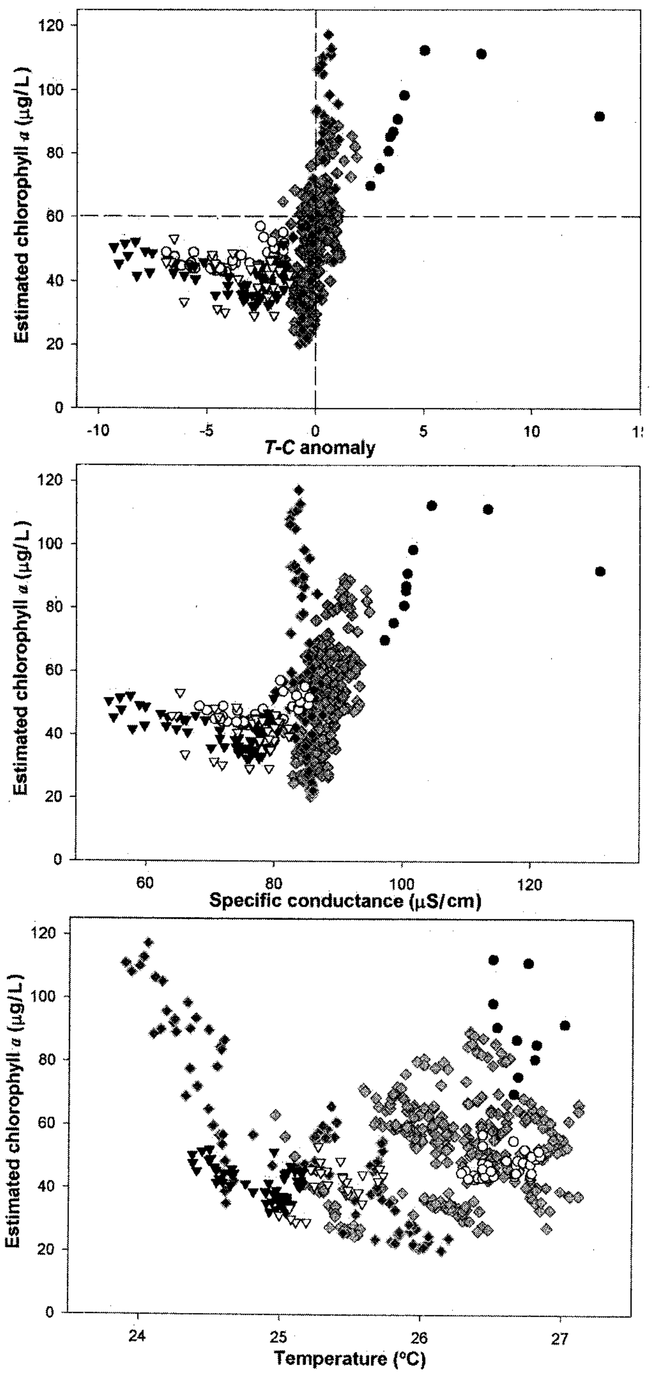

Figure 5. Relationship between estimated chlorophyll-*a* and the different physical-chemical variables (*T*, *C*, and A_{TC}) obtained during the coastal trawling. A cluster analysis (Ward's method with city block distance) was used to classify the data cloud of *chl**-A_{TC} in three clusters. Dashed lines represent the centroid of the central cluster, characterized by values of A_{TC} near zero and moderate *chl**. The other two clusters corresponded with the data in the upper right (high positive A_{TC} and high *chl**) and lower left (high negative A_{TC} and low *chl**) quadrants. See Figure 2 for symbol definition.

hampers an efficient removal which occurs in other large wetlands. Water flow is $100 \cdot 10^6$ m^3/year [*Balirwa and Bugenyi*, 1988], representing a considerable water entry in Lake Victoria. Thus the wetland linked to Katonga Bay is not capable of reducing the concentration of dissolved substances of the inflowing waters to the same extent as other wetlands receiving a smaller water flow. These results demonstrate that the ratio for matter discharge through the wetland to area of wetland may be a more relevant parameter than the wetland area per se. This fact is not clearly revealed using only conductance measurements because Katonga Bay showed relatively low *C* similar to other bays linked to large wetlands (Figure 1). Warmest or coldest waters are not necessarily associated to irregular *C* values if we consider the *T-C* linkage (Figure 2).

[21] A complete description of water mass movement requires horizontal property distributions as well as vertical sections. Depth profiles of *T* and *C* also demonstrate the utility of A_{TC} throughout the water column (Figure 4). The high-resolution grids of A_{TC} profiles were used to track the upland water intrusions within the bays. The outflowing from the large wetlands was often located near the bottom, in deep layers with a slightly lower A_{TC} (around 1 unit). The expanse of the wetlands was also related to the persistence of the water intrusions into the lake. The horizontal length of the water intrusions was several kilometers higher in the bays with large wetland. In the disturbed Inner Murchinson Bay, vertical differences of A_{TC} were more discernible (between 1 and 60 units), especially at the Wankolokolo and Nakivubo wetland outlets. In the deep water layer, we found positive anomalies. Wankolokolo stream drains the northeastern side of Kampala city before flowing into its wetland area. Nakivibo wetland directly receives partially treated and untreated wastewater from Kampala city, showing the highest *T-C* anomalies found in this study ($A_{TC} = +94$).

[22] Temperature and specific conductivity are mainly related to the physical-chemical characteristics of the water. Changes in pH due to the photosynthesis and respiration could induce some indirect variation in conductance; however, biological activity would only rarely modify significantly these properties. Nevertheless, to study the possible relationships of A_{TC} with the ecological characteristics of the lake, the simultaneous measurements of *chl** were compared to the A_{TC} parameter. Despite the different factors intervening in the final phytoplankton concentration (e.g., nutrients, light, grazing), A_{TC} showed a striking correlation with the *chl** concentration (Figure 5). High absolute values of A_{TC} were found where extreme conditions of phytoplanktonic biomass are present. Strongly negative A_{TC} (<-1.5; e.g., wetland waters) were linked to relatively low *chl** concentrations, while high positive A_{TC} ($>+1.5$; e.g., disturbed watershed) were found in areas of high *chl** concentrations. Anomalies near zero (between -1.5 and $+1.5$) showed a wide range of *chl**, but even small decreases or increases from zero showed a significant tendency of the inshore waters to contain low or high *chl** respectively. Therefore the sign of A_{TC} is related to trophic conditions. A_{TC} showed also a stronger correlation to the biological community than either *C* or *T* (Table 1). Conductance measurements can explain the general trophic pattern than can be observed using A_{TC}. However, the correlation

Table 1. Pearson Correlation Between *chl** and Different Physical-Chemical Variables (Temperature, Specific Conductance, and *T-C* Anomaly) in the Data Sets of Katonga Bay (KB), Open Shoreline (OS), and Their Combination (KB + OS)[a]

	chl^*_{KB}	chl^*_{OS}	chl^*_{KB+OS}
T	−0.87	+0.12	−0.26
C	−0.43	+0.55	+0.20
A_{TC}	+0.73	+0.59	+0.59

[a]Katonga Bay was separately analyzed due to its cold water temperatures. A_{TC} showed significant positive linear correlations (anova; $P < 0.01$) for all data sets.

between C and *chl** is modified when high variations of T occur (Figure 5). Very cold or very warm temperatures are not necessary related to irregular *T-C* values (Figure 2).

[23] Using a gross spatiotemporal resolution (9×9 km^2 and 1 month), the surface temperatures derived from MODIS satellite imagery (from August 2003 to April 2004; NASA archive) showed a variation of 11.9°C (from 18.9 to 30.8°C) in the Lake Victoria surface waters. This difference is much larger that observed in the present transect measurements. A large thermal variability would produce significant differences in evaporation rates and specific conductivity of the surface waters, which hamper the uncombined analysis of this variable.

5. Conclusion

[24] The combined use of T and C in TC diagrams provides a more robust characterization of the inshore waters than the analysis of the single variables. Temporal variability of both T and C hampers the use of only one of these parameters for spatial comparison, especially in the surface waters. TC diagrams allow considering drift patterns of T and C due to heat and matter fluxes. Additionally, together T and C govern the water density, which is the major factor controlling the water movements. The construction of TC diagrams is usually feasible as these parameters are commonly obtained simultaneously in the limnological studies.

[25] The A_{TC} parameter offers a complementary specific tracing of the upland water masses. The sign and value of A_{TC} may be used to analyze the influence of the catchment on the water runoff. Water masses located in the open shoreline and bays with little or no wetland showed values of A_{TC} near zero. Coastal areas with watersheds characterized by farming or urbanization were associated with the presence of irregular water masses with highly positive A_{TC} (>+1.5). The filtering capacity of extensive wetlands areas was reflected in negative A_{TC} (<−1.5). This parameter showed also a stronger connection with the simultaneously estimated chlorophyll-*a* concentrations than either T or C.

[26] In Lake Victoria, the use of the A_{TC} parameter highlighted the role of wetlands in the physical-chemical and ecological characteristics of the inshore waters. The indented morphology of the Lake Victoria coastline includes abundant semiclosed bays that could magnify the effects of the growing eutrophication [*Muggide*, 2001]. Results show that the wetland ecotones that border these bays play an important role in regulating the flow of matter from the catchment to the lake waters. The role of the wetlands was evident in the southern part of the studied shoreline (with extensive wetlands), where A_{TC} was negative or nearly zero. The positive values of A_{TC} in Murchinson Bay, however, demonstrate that the ionic retention capacity of the small Nakivubo and Wankolokolo wetlands is being exceeded. The filtering capacity of these wetlands certainly contributes to the partial treatment of the agricultural and urban water intrusions. However, under the growing pressure from human activities, the integrity of these wetlands is being compromised. In Nakivubo, a large percentage of the former papyrus wetland has been converted to subsistence root crops. In other areas of Lake Victoria, wetlands are being converted into areas of intensive agriculture (Yala wetland, Kenya). Encroachment is a growing problem in many littoral areas. Any conversion of wetlands that compromises their structural or functional integrity should be considered in the research and management of the Lake Victoria inshore waters.

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N. Azza, Directorate of Water Development, P.O. Box 19, Entebbe, Uganda. (azza.wrmd@dwd.co.ug)

L. Bracchini, A. Dattilo, and S. Loiselle, Dipartimento di Scienze Chimiche e dei Biosistemi, Università di Siena, Via Aldo Moro 2, I-53100 Siena, Italy. (bracchini@unisi.it; dattilo@unisi.it; loiselle@unisi.it)

A. Cózar, Área de Ecología, Facultad de Ciencias del Mar, Universidad de Cádiz, E-11510 Puerto Real, Cádiz, Spain. (andres.cozar@uca.es)