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RESEARCH ARTICLE

EFFECTS OF PH AND SALINITY ON THE SEDIMENTATION OF CLAY PARTICLES IN TURBID LAKES OF THE RIFT VALLEY OF ETHIOPIA AND KENYA

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ABSTRACT: Some lakes in the Rift Valley of East Africa are among the most productive in the world, while others are dystrophic, possessing a stable, opaque suspension of fine silt or clay. Understanding the causes of flocculation and sedimentation of this material could provide insight into why these lakes are so turbid. We collected samples of suspended clay from three turbid lakes (Langano and Abaya in Ethiopia, and Baringo in Kenya), measured the size-distribution and organic content of their suspended sediment, and performed laboratory studies of sedimentation rate as a function of pH and salinity. Most of the turbidity in the two Ethiopian lakes was due to particles between 0.5 and 1.5 µm, and the suspended material had a low organic content and C/N ratio in all the three lakes. Sedimentation velocity of the material increased with both salinity and pH, with velocities varying from near 0 at neutral pH and low salinity, to 3 cm h^{-1} as pH approached 12 or salinity approached 25 ppt in the case of Lake Abaya. These results may explain why it is only freshwater lakes that demonstrate these turbid clay suspensions, and suggest mechanisms through which their turbidity might be altered.

Key words/phrases: Abaya, Baringo, Clay, Lake restoration, Langano, Sedimentation, Turbidity.

INTRODUCTION

The Ethiopian and Kenyan Rift Valley lakes include some of the most productive lakes in the world (Talling *et al*., 1973). Many provide drinking water and are important for fisheries, irrigation and recreation. Others are saline or severely turbid and dystrophic, possessing a stable suspension of fine sediment (Taylor *et al*., 2002). The turbid lakes are freshwater, and hence potentially very valuable in this arid and poor region (Mepham *et al*., 1992). Much of the land surrounding the lakes has been harvested for trees to make way for agricultural production and to provide wood for fuel

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(Zinabu Gebre-Mariam, 2002). Some are in areas that have been overused by pastoralists for their livestock, especially goats, which graze the sparse vegetation and loosen the soil (Aloo, 2002). All of this contributes to soil erosion in the catchments, causing suspended solids to enter the lakes (Zinabu Gebre-Mariam, 2002). Although riverine samples were not subjected to particle size analysis in this study, much of the suspended sediment in the lakes appear to fine (< 2 mm) with silt and clay particles as the dominant forms.

Turbid Rift Valley lakes, including Langano, Abaya, and Baringo, have low chlorophyll *a* concentrations (Taylor *et al*., 2002) and light attenuation in these lakes appears to be due largely to their suspended sediments. Even in the relatively productive L. Abijata (downstream of Lake Langano) only 22% of light attenuation was attributable to algae (Wood *et al*., 1978). While historical data are few, accounts of Lakes Langano and Abaya in the late 1930's (Vatova, 1940; Zanon, 1941; Cannici and Almagià, 1947) describe them as turbid and yellowish due to silt. The transparency of Abaya (referred to in these papers as Lake Margherita) was given as < 0.5 m. The lakes are now brown in colour, and still have Secchi depths less than 0.5 m (Elizabeth Kebede *et al*., 1994). Lake Baringo was described earlier as greenish in colour due to cyanobacteria (Copley, 1948, cited in Aloo, 2002).

Suspended particles can decrease light attenuation by both scattering and absorbing light. Weak stratification and low light penetration reduce the light available for photosynthesis in the mixed surface layer, thereby decreasing the phytoplankton density as well as primary and secondary productivity (Cuker, 1993; Taylor *et al*., 2002). Low rates of photosynthesis further decrease the already low dissolved oxygen concentration in these warm waters (Cordone and Kelley, 1961). Besides low primary production and oxygen, turbidity adversely affects fish by limiting the capture success of visual predators, reducing the efficiency of respiration (Pekcan-Hekim and Horpilla, 2007), and changing visual behaviour including aggressive interactions (Gray *et al*., 2012) and sexual selection (Seehausen *et al*., 1997). The impact of fine sediment on benthic macroinvertebrates has been reviewed by Wood and Armitage (1997).

The stability of colloidal suspensions is largely controlled by ionic strength, the type of ions present and pH (Goldberg *et al*., 1991; Tombacz *et al*., 1998). Clay particles have a negative charge on their surfaces, and in water they attract positive ions with balancing charges that allow the particles to maintain their neutrality. This results in the formation of a positive layer around each clay particle. Van der Waal's forces dominate the attraction between particles, but electrostatic forces repel because of a positive layer of counter ions. The relative strength of these opposing forces is affected by pH and the concentration of other ions. Dominance of Van der Walls's forces lead to flocculation, which is also affected by organic matter and particle density. High salinity and pH can increase the particle-particle interactions and enhance aggregation rates due to the compression of the electrical double layer at high salt concentrations as the clay-bound cations diffuse away into the solution which causes a charge reduction of the particle (Goldberg *et al*., 1991).

Flocculation increases particle size and therefore enhances settling rates, as predicted by Stoke's Law (Håkanson and Jansson, 1983). Previous studies suggest water chemistry and particularly pH have a large effect on the rates of aggregation (e.g., Tombacz *et al*., 1998; Kim and Nestmann, 2009). Salinity may have a large impact as well, but that impact is more dependent on other chemical properties of the water (Kim and Nestmann, 2009). Increasing pH or salinity may increase the density of the flocs in relation to the density of the water, contributing to the increase in sedimentation rates (Selley, 2000).

The lakes of the Rift Valley display a range of alkalinities and salinities, and those with closed basins may have very high values (Table 1). The dominant ions in these lakes are typically Na^+, CO_3^{2-} and HCO_3^-, and most "salinities" reported in the literature are estimated from conductivity. Baxter (2002) reviewed the chemistry of the Ethiopian lakes, including earlier investigations on the relationship of chemistry to the precipitation of the suspended colloidal material in Lake Langano. Specifically, on raising the salinity of water from freshwater and turbid Lake Langano to that of saline Lake Shalla, the "silt" quickly precipitates (Wood *et al*., 1978; Amha Belay and Wood, 1984) as it also does if the water is diluted. One of us (ZGM) observed that raising the pH of Langano water would also cause precipitation.

The turbid Rift Valley Lakes display relatively low salinities, alkalinities and pH values relative to other lakes in this part of the rift (Table 1). Therefore, we hypothesize that lakes with waters higher in pH and salinity may not support stable clay suspensions, whereas freshwater lakes with near-neutral pH are more susceptible to becoming turbid. As a first step in further developing this hypothesis, this paper examines the settling velocity of clay particles collected from three turbid Rift Valley lakes in gradients of pH and salinity under laboratory conditions.

METHODS

Water samples were obtained from three turbid Rift Valley lakes in 2002. Lake Langano was sampled on November 9 approximately 700 m off the western shore of the lake. Lake Abaya was sampled on November 10 from the end of the stone jetty at the crocodile farm at Arba Minch in the southeast corner of the lake. Lake Baringo was sampled on November 14 off its western shore near the Kenya Marine and Freshwater Research Institute (KMFRI) at what a fisherman reported was the deepest part of the lake. However, with very low water levels at the time, the site was only 1.5 m deep. Samples from Lakes Langano and Abaya were returned to Hawassa University, Hawassa, Ethiopia, for processing, while samples from Lake Baringo were returned to Egerton University in Njoro, Kenya. Characteristics of these lakes and other lakes in the area are provided in Table 1.

Table 1. Characteristics of some Rift Valley lakes, including the three turbid lakes used in this study marked with an *. Conductivity (Cond, K25) is in µS cm^{-1}, Na^+ and Alkalinity (HCO_3^+ CO_3) are in meq l^{-1}, and chlorophyll-*a* is in µg L^{-1}. Mean chemistry values for the study period 1990–2000 for the Ethiopian lakes are from Zinabu Gebre-Mariam *et al*. (2002). Depth data for Ethiopian lakes are from Baxter (2002). Chemistry data for the Kenyan Lakes (last 3 rows) are means during 1998–1999 from Yasindi *et al*. (2007) except + is from Mugo (2010).

Lake	Mean depth	Cond	Na^+	pH	Alkalinity	Chlorophyll-*a*
Ziway	2.5	388	2.8	8.5	4.1	82.4
Hawassa (Awassa)	10.7	846	7.1	8.8	7.8	23.4
*Abaya	7.1	921	9.2	8.7	8.6	8.2
Chamo		1568	14.7	9.2	13.3	100.3
*Langano	17	1588	16.6	9.0	12.2	14.3
Shalla	87	22863	289	9.7	217.3	11.2
Abijata	7.6	26360	311	9.9	266.6	62.1
*Baringo	4.4	912		8.2	233	43
Bogoria	7	69792		9.4	14317	266
Naivasha	4.1+	319		7.8	50	26

Within 24 h of sampling, 50 to 200 mL aliquots of lake water were filtered onto 47-mm glass-fibre filters (GF/F 0.8 µm pore size) for analysis of particulate organic carbon (POC) and particulate organic nitrogen (PON) using a CEC-440 elemental analyzer (Exeter Analytical Inc). A second set of filters from all samples were pre-weighed, dried, weighed again, ashed and re-weighed for determination of suspended solids and ash-free dry weight. The size of particles contributing to turbidity of water from Lakes Abaya and Langano was characterized by filtering aliquots through 0.2, 1.0, 2.0 and 3.0 µm pore-size polycarbonate membranes and measuring the absorbance of the filtrates at 750 nm. We were unable to do this sizefractionation for Lake Baringo due to the lack of a spectrophotometer. Samples from all lakes were then adjusted to elevated pH in 2-L graduated cylinders with 1 N NaOH. The relationship between base added and pH was recorded. Precipitation of the suspended materials was sudden and obvious to the naked eye at high pH. We removed the clear supernatant by aspiration and collected the flocculated particulate matter into 20-mL glass scintillation vials, added formaldehyde to prevent decay of any organic matter, and returned the samples to University of Waterloo.

Experiments on the effect of salinity and pH on sedimentation of the particles collected above were performed between November 2010 and February 2011. Aliquots of sediment were re-suspended in de-ionized water and transferred into 100-mL graduated cylinders. The pH of the sediment samples was altered using dropwise addition of 1 M NaOH or HCl and a pH meter to create 8 different pH levels in a gradient between 6.5 and 12.5. Salinity manipulations were similar, using additions of 2.5% $NaHCO_3$, Na^+ and HCO_3^- being the dominant ions in these lakes, to generate a salinity gradient for testing between 0 ppt and 25 ppt. Eight different salinities were created within this range, and conductivity measurements were taken to ensure the salt solution created the desired gradient. Conductivity of these samples ranged from approximately 18 to 20,000 µS cm^{-1}. The pH of these solutions was not determined.

The solutions were prepared and left to settle for approximately 50–60 min. Preliminary experiments (not shown) demonstrated that 50–60 minutes of settling produced a quantifiable decline in turbidity in the top 45 cm of the cylinders. Allowing too long an incubation time would deplete the particles in the top half of the graduated cylinder and cause underestimation of the settling velocity, whereas too short a time would result in too small a change to quantify. After allowing the cylinders to stand undisturbed, the top 45 mL was aspirated using a vacuum pump. Samples from the top 45 mL and the bottom 55 mL were agitated then measured for turbidity, allowing for the calculation of settling velocity (cm h^{-1}) as in Burns and Rosa (1980). Pictures of the particles were taken with a Zeiss compound photomicroscope.

RESULTS

The addition of NaOH to field-collected samples produced an increase in pH (Fig. 1). The increase in pH was initially buffered, but after the addition of about 1 N NaOH the pH began to rise to 12 and beyond. Thereafter, precipitation of the turbidity occurred and the precipitate was collected as described above.

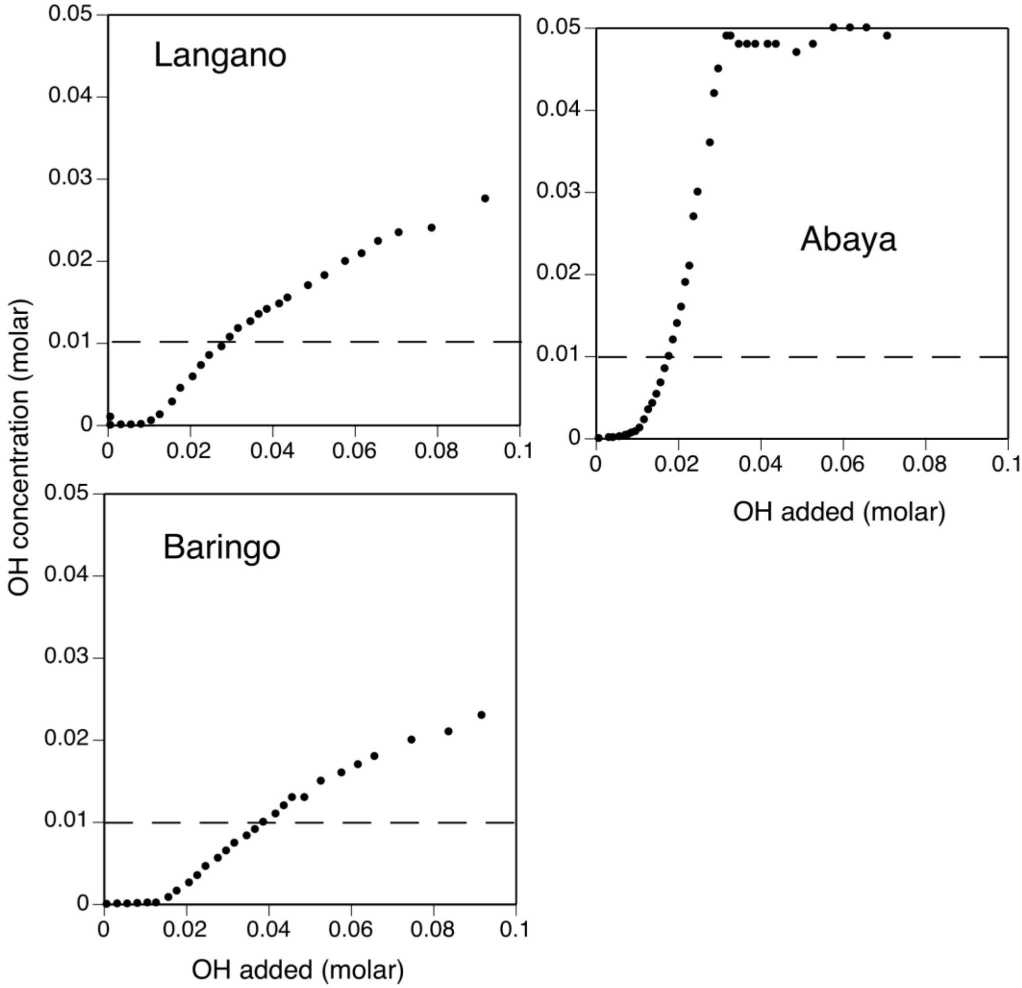

Fig. 1. The change in pH with amount of OH added for three Rift Valley lakes. The horizontal dashed line indicates the OH concentration at which pH = 12.

The particulate material collected from the lakes onto GF/F filters varied greatly in concentration (Table 2), but was similar in having a low organic content (3–4.4%) and a low C/N ratio (8.5 to 9.4). The particles contributing most (>80%) to the turbidity of waters from Lakes Abaya and Langano were in the clay size-range of 0.2 to 2 µm. The turbidity from Lake Langano was due to finer particles than that of Lake Abaya (Fig. 2).

Table 2. Characteristics of the suspended material from three turbid Rift Valley lakes.

Lake	TSS (mg/L)	Part C (mg/L)	Part N (mg/L)	C/N	% Organic
Langano	103	1.6	0.17	9.4	3.91
Abaya	136	2.4	0.28	8.6	4.38
Baringo	932	11.3	1.33	8.5	3.03

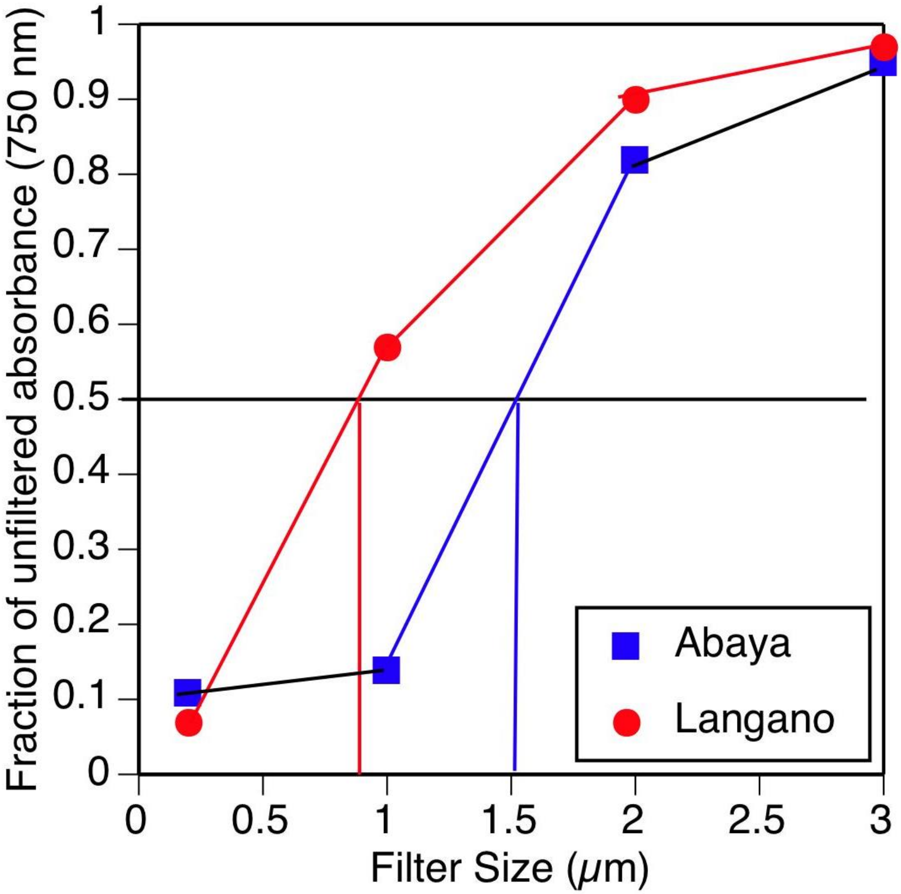

Fig. 2. Fraction of total turbidity (measured as light attenuation at 750 nm) in filtrates from Lake Abaya and Langano produced with different sized polycarbonate filters. The horizontal line indicates 50% reduction in turbidity, while the vertical lines indicates the corresponding particle sizes for the two lakes.

For all three lakes there was an accelerating relationship between sedimentation velocity and pH for the particles collected by precipitation (Fig. 3). Estimates of sedimentation velocity also increased with salinity

(Fig. 4). These relationships were approximately linear, allowing us to use linear regressions and analysis of covariance (ANCOVA). Linear regression estimated sedimentation velocities at 0 salinity to be from near zero for Baringo (0.03 cm h^{-1}) and up to 0.442 cm h^{-1} for Langano (Fig. 4). All three relationships were significant ($p<0.05$). At salinity of 25 ppt, estimated velocities ranged from 0.90 for Langano to 3.06 cm h^{-1} for Abaya. ANCOVA indicated that the slopes of the relationships between salinity and sedimentation velocity varied among lakes, with Lake Langano having a significantly lower slope, and confirmed that salinity was a significant covariate of sedimentation velocity ($p<0.001$). Microscopy confirmed that particles were aggregated into much larger flocs at high pH or salinity (Fig. 5).

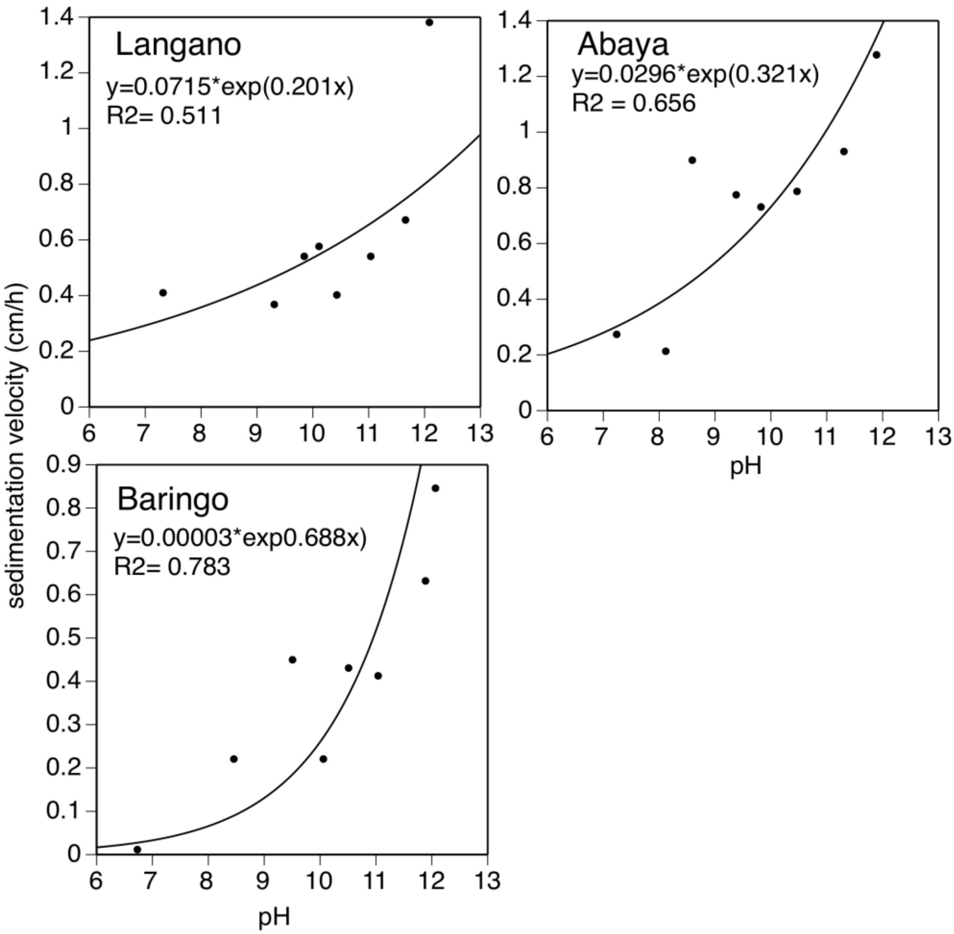

Fig. 3. Sedimentation velocity of particles in Lakes Langano, Abaya and Baringo as a function of pH.

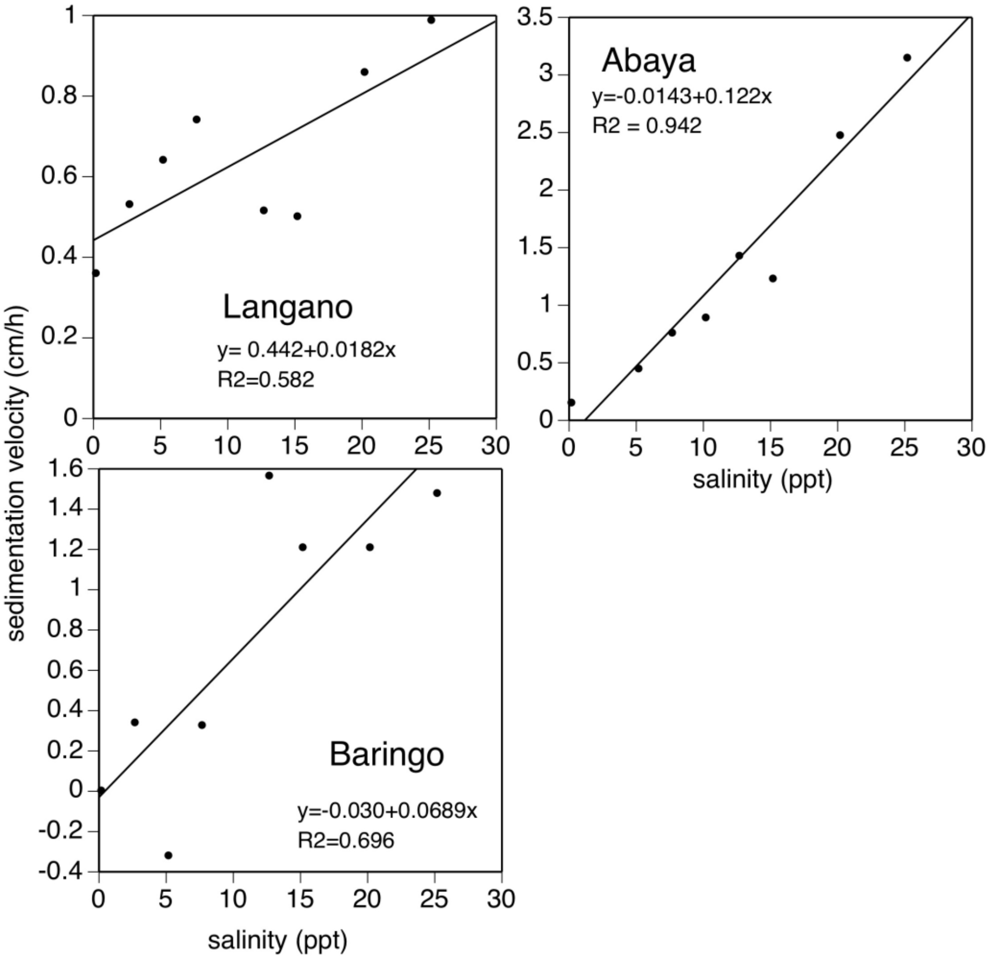

Fig. 4. The relationship between settling velocity and salinity for fine particulate matter from three Rift Valley lakes. Note the differences in scale on the y-axis.

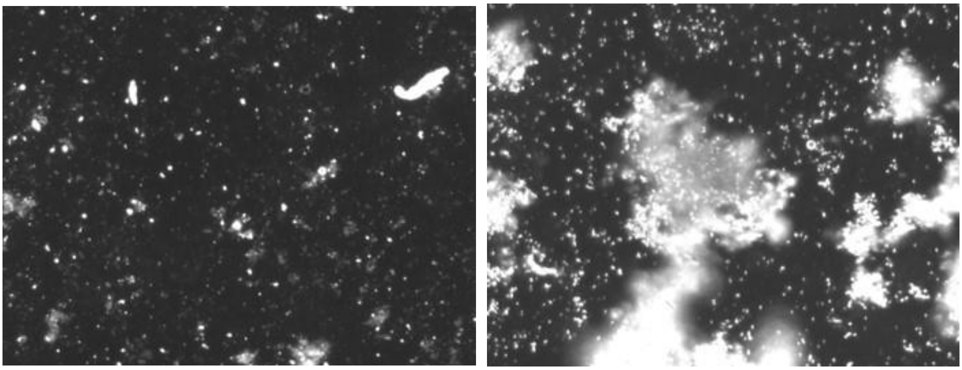

Fig. 5. Lake Langano particles photographed at 1000X magnification at pH 7 (left) and pH 12 (right).

DISCUSSION

Settling velocities of the particles we collected from the lakes, initially by pH-induced precipitation, increased with both pH and salinity in laboratory experiments. Salinity and pH are correlated among the Rift Valley lakes (Yasindi *et al*., 2007). Not only did we confirm that radical shifts in pH or salinity can cause precipitation, but also that sedimentation velocity of the particles causing turbidity varies with these variables over the ranges observed in the field among these lakes. Our observations support the hypothesis that fresh water lakes in the Rift Valley are more likely to maintain high turbidity when clay is transported to them by erosion in the catchment.

Another way of looking at this hypothesis is by looking at nearby lakes with contrasting properties. For example, Lake Abijata is downstream of turbid Lake Langano and has a conductivity of ~25000 µS cm^{-1} (Table 1) compared to Langano's ~1600 µS cm^{-1} but is eutrophic with high phytoplankton biomass. Similarly, Lake Bogoria, which is downstream of Lake Baringo, and has a conductivity of ~70,000 µS cm^{-1} as opposed to Baringo's ~900 µS cm^{-1} (Table 1) and has much higher phytoplankton biomass. Neighbouring Lakes Chamo and Abaya with conductivity of ~1600 and 900 µS cm^{-1}, respectively, exhibit sharp contrast where Lake Chamo (which is downstream of Lake Abaya although currently isolated from it), is highly productive while Abaya is dystrophic. In this case, the differences in conductivity are relatively small. If the difference in turbidity is due in part to conductivity and its effect on clay behaviour, then dilution of Lake Chamo might put it in danger of becoming turbid and dystrophic rather than eutrophic. Fortunately, it is rather remote and much of its shoreline is protected by Nechisar National Park.

A second factor that might help to explain why some saline lakes are eutrophic rather than dystrophic despite high turbidity would be that their high nutrients and shallow depth allow greater phytoplankton production and biomass despite the turbidity. As mentioned above, Wood *et al*. (1978) could only account for 22% of the turbidity of saline and eutrophic Lake Abijata, which is downstream of Lake Langano (and Ziway), by phytoplankton. The high phytoplankton biomass in Lake Abijata might occur despite high mineral turbidity because the mean water column light is still adequate due to its shallowness. On the other hand, Lakes Langano and Lake Abijata have somewhat similar mean depths (7.1 and 7.6 m) so the higher salinity of Lake Abijata may be a critical factor.

Apart from pH and salinity, water movement leads to suspension of fine sediments and depends on several other factors including wind velocity, fetch, wave height, sediment properties, and depth profile (Håkanson and Jansson, 1983; Evans, 1994). In addition to wave action, sediments can also be resuspended by animals (Andersson *et al*., 1988). Fish may stir up sediments, increasing the concentration of suspended solids. All the three lakes we sampled have fish (and Abaya and Baringo have hippopotamus) but their contribution to turbidity in these lakes is unknown.

Relationships between sedimentation and ionic composition of the water have been observed in other systems, depending on the composition of the particles, as the conditions for coagulation and the stability of aggregates will greatly depend on the net particle charge as affected by ionic strength, pH and the specific ions present (Goldberg *et al*., 1991; Chorom and Rengasamy, 1995). The pH dependence of the aggregates will also vary depending on the clay composition (Goldberg *et al*., 1991; Tombacz *et al*., 1998). Sodium-based clays have shown decreasing aggregation and increasing dispersion with increasing pH, as the negative charge of the clay particles increases (Arora and Coleman, 1979; Chorom and Rengasamy, 1995). Calcium-based clays on the other hand were shown to exhibit a positive correlation between flocculation and pH, similar to observations in this report, at pH greater than 7. This occurs as calcium carbonates begin to form, coating the clay particles and reducing their overall charge; allowing for flocculation (Chorom and Rengasamy, 1995). Calcium carbonates have been examined in terms of their ability to increase flocculation (Gupta *et al*., 1984; Amézketa, 1999). The water chemistry of most Rift Valley Lakes has been described as sodium bicarbonate and carbonate dominated, depending on pH, with little contribution from the divalent cations calcium and magnesium (Wood and Talling, 1988; Baxter, 2002).

The sedimentation velocities we observed were in the range of 0 to 3 cm h^{-1}, comparable to sedimentation velocities of particulate matter and individual phytoplankton observed in temperate lakes (e.g., Bloesch and Sturm, 1986; Horn and Horn, 1993). For a 5 m water column, the residence time of particles at the high end of this range would be 7 days.

Further research on this topic could include better characterization of the clay particles and their interaction with ions, and studies using lake water directly taken from the lakes rather than particles that have been precipitated and re-suspended. Paleolimnological studies might be able to shed some light on the history of the lakes, when they became turbid, and what land use or other changes were associated. From an applied perspective, experimental enclosures in which ion concentrations could be manipulated would be very interesting. They could lead the way to opportunities for aquaculture in these otherwise unproductive lakes, and possibly to attempts at lake restoration.

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