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Radioisotope and metal content in a Lake Nakuru sediment core – accumulation rate and inventories
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Abstract:	The Nakuru environment is a hot spot both for human population and for biological conservation with a large number of species protected in the well visited Lake Nakuru National Park. Reoccurring mass die-off of the Lesser Flamingo in Lake Nakuru as well as cases of intoxication of humans within the water catchment area have gained attention and dedicated a significant amount of research over the recent decades. The toxicological histories of natural and anthropogenic activities are reflected by accumulated compounds in the water body sediments. In this study, a sediment core obtained from the central and deepest point of Lake Nakuru was sliced with 5 mm resolution and analyzed with the 210Pb dating method. The results show a linear accumulation rate of 1.3 mm y-1 and a mass accumulation rate of 0.027 g cm-2 y-1. Further analysis resulted in core profiles of organic material decay, phosphorus concentration gradient and total content of heavy metals in the lake water and in the sediment. In addition, analysis of 226Ra, 137Cs, 239+240Pu, 228Th/232Th was performed.
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1 **Title:**

2 Radioisotope and metal content in a Lake Nakuru sediment core – accumulation rate and
3 inventories

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17 conservation with a large number of species protected in the well visited Lake Nakuru
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21 of natural and anthropogenic activities are reflected by accumulated compounds in the water
22 body sediments. In this study, a sediment core obtained from the central and deepest point of
23 Lake Nakuru was sliced with 5 mm resolution and analyzed with the ^{210}Pb dating method.
24 The results show a linear accumulation rate of 1.3 mm y^{-1} and a mass accumulation rate of
25 0.027 g cm^{-2} y^{-1}. Further analysis resulted in core profiles of organic material decay,
26 phosphorus concentration gradient and total content of heavy metals in the lake water and in
27 the sediment. In addition, analysis of ^{226}Ra, ^{137}Cs, $^{239+240}$Pu, ^{228}Th/^{232}Th was performed.

28

1 **Introduction**

2 Lake Nakuru is a closed basin hypereutrophic alkaline salt-water lake in Kenya. It symbolizes
3 a biological hot spot exhibiting a large number of species concentrated to a small area that is
4 protected within Lake Nakuru National Park, which in turn is one of the most visited national
5 parks in Kenya. Amongst the ~400 bird species observed, the most spectacular often refers to
6 the large numbers of Lesser Flamingo (*Phoeniconaias minor*) that occasionally can add up to
7 several hundred thousands of birds. (Vareschi, 1979) The large primary production in the
8 alkaline saline lake constitutes a feedstock of algae where in particular the cyanobacterium
9 Spirulina (*Arthrospira fusiformis*) comprises the main food source for the Lesser Flamingo.
10 (Vareschi, 1978, 1979, 1982, 1984a, 1984b, 1985, 1987; Nogrady 1983)

11 The abundance of Lesser Flamingo is naturally fluctuating but after observations of
12 mortalities with >10,000 birds involved during the years 1993, 1995, 1999, 2001, 2006 and
13 2008 (Krientiz and Kotut, 2010), flamingo ecology have been devoted a significant amount of
14 research. Flamingo health and mortality have been addressed to fluctuation in algae crop,
15 toxins associated with other species of naturally occurring cyanobacterium, organic toxins or
16 heavy metal pollution originating from human activities. (Greichus et al., 1978;
17 Krientiz et al., 2016)

18 The water catchment area in the Lake Nakuru basin is estimated to 1938 km^2 (Greichus et
19 al., 1978) and by planar projection to 1800 km^2 (Vareschi, 1982). The basin comprises the
20 Lake Nakuru National Park of 188 km^2 (KWS, 2017) wherein the Lake Nakuru covers
21 approximately 60 km^2 (Schultz and Zabel, 2000). The remaining area is to the majority
22 represented by a densely populated country side with farms and villages, with little forest
23 cover. Consequently, erosion facilitates mobility of potential toxic compounds from
24 precipitation or human origin. The large regional city of Nakuru having about 260 000
25 inhabitants (WPR, 2017) is located about 1 km from the lake shores and has two sewage
26 treatment plants draining into the lake. The main road between east Africa's coastal port city
27 of Mombasa, via Nairobi and further to the African inland via the Uganda capital city of
28 Kampala passes through the city with heavy commercial traffic that increase air pollution as
29 well as pollution from vehicle tyres and oil products. During the last century, leaded petrol
30 was used. Nakuru has a history of developed industrial production, including textile, battery,
31 tannery and galvanizing industries. (Vareschi, 1978) Toxic compounds originating from
32 anthropogenic activity resulting in human toxicity have been identified in the water catchment
33 area and targeted for investigations. (Odongo et al., 2016)

34 Lake Nakuru is a shallow saline pan with an average depth slightly below 1 m, it has no
35 outlets and is regulated by precipitation within the water catchment basin and evaporation,
36 thus the lake surface area varies between ~45 - 60 km^2. The area around the lake is
37 accordingly flat and has in historical time constituted lake bottom as a part of a larger lake
38 including Lake Elementaita and Lake Naivash. Furthermore, the area has on a geological
39 timescale received extensive volcanic activity. (Vareschi, 1982) Over time, dissolved
40 organic- and inorganic compounds as well as particulate matter have accumulated to compose
41 the alkaline salt lake and its sediment. (Schultz and Zabel, 2000; Stumm and Morgan, 1996;

Schlargerl and Burian, 2016) The deepest part, around 2-5m deep depending on surface water level, centered in the lake corresponds to the final deposition point in the basin thus representing the historical archive for compounds of natural and anthropogenic origin. (Schultz and Zabel, 2000; Appelby and Oldfield, 1978; Koide et al., 1973; Christensen and Chien, 1981)

In order to evaluate any time trend in the environment affecting the lake, it is useful to try and extract data from a sediment profile. Sediment chronology can often be established either by using well documented events (*e.g.* tephra layers from known volcano eruptions or excess ^{137}Cs from the Chernobyl NPP accident in 1986) or by applying radioisotope techniques based on isotopes in the natural decay chains originating from the [238]U, [235]U and [232]Th decay.

The earth's content of [238]U originates from when our planet was formed and the nuclide has a half-life of 4.6 million years. One decay product is [222]Rn which is a noble gas and diffuses from the ground to the air with a constant flux, but because of its short half-life of 3.8 days, the particle reactive daughter nuclide ^{210}Pb with a half-life of 22.86 years is washed out from the atmosphere and re-deposited to the ground, particularly during precipitation. The ^{210}Pb may thus be mobilized with surface water run-off due to the main inventory of ^{210}Pb is associated to small size mobile particles. Because of the small area of a deposition bottom in a lake compared to the lake's water catchment area, ^{210}Pb, like other pollutants from atmospheric deposition, will often become accumulated with a higher concentration in the bottom sediments at the deepest point such as in the basin located in Lake Nakuru. The ^{210}Pb found in the sediment accumulation areas thus originate both from direct deposition on the lake surface and due to focusing from surrounding lake sediments and catchment run-off. If this process is appearing at a relatively constant rate so that the atmospheric deposition is constantly balanced by the removal due to erosion and radioactive decay, the system is in equilibrium, for ^{210}Pb with a half-live of 22 years such an equilibrium system takes roughly some 60 to 70 years to develop. The amount of ^{210}Pb at a given surface area of the sediment will then be constant with time and a depth profile will show a gradient with a slope only depending on the sediment accumulation rate (cm per year or g per m^2 and year). Therefore a method for determining chronology in stratified sediment is by analyzing ^{210}Pb activity with sediment depth. (Appelby and Oldfield, 1978; Bollhöfer et al., 1994; Blais et al., 1995; Matthews et al., 2007; Brown et al., 2011)

The isotope [232]Th with a half-life of 10^{10} years occurs naturally in the earth's crust. Thorium in aqueous solutions quickly hydrolyses and attaches to any surface thus making its residence time in lakes and oceans very short. The daughter isotope [228]Ra (5.8 years half-life) on the other hand is considerably more mobile and may migrate from soils to lake reservoirs where it eventually decays to the short lived [228]Th. The daughter nuclide [228]Th with a half-life of 1.9 years share the same chemical properties with [232]Th and thus becomes attached to particles and thereby transfer into the sediments. Although the [228]Th / [232]Th ratio in soils may be less than 1 (due to the [228]Ra migration) it is often larger than 1 in surface sediments due to the excess input of [228]Th from [228]Ra decay. This allow for using the [228]Th / [232]Th as a measure of sediment accumulation rates in recent time scale of approximately 10 years of age.

1 Naturally occurring ^{137}Cs and $^{239+240}$Pu exist in concentrations below detection levels, thus the

2 measurable contents originate from human activity. The period corresponding to nuclear

3 bomb injection of these isotopes into the earth's atmosphere corresponds to 1950-1960's with

4 a peak around 1963. The Chernobyl nuclear plant disaster in 1986 left a measureable peak of

5 ^{137}Cs in the northern hemisphere. The re-entry of the satellite Snap-9A in 1964 caused a

6 significant injection of ^{238}Pu from its evaporated radioisotope battery exclusively in the

7 southern hemisphere. (Hardy et al., 1972; Levy et al., 2011). The analysis of the above-

8 mentioned radioisotopes in a sediment core thus may provide information about the sediment

9 accumulation rate or its mixing since the inputs are well described in time.

10 In this study we have collected a sediment core from the center deposition bottom in Lake

11 Nakuru that was analyzed to obtain 1) activity profiles of ^{210}Pb, ^{226}Ra, ^{137}Cs, $^{239+240}$Pu,

12 ^{228}Th/^{232}Th, 2) concentration profiles of organic material and phosphorus and 3) content of the

13 heavy metals Cd, Cr, Cu, Hg, Ni, P, Pb and Zn.

14 **Materials and methods**

15 <u>Site description and sampling</u>

16 The sediment core was sampled in Lake Nakuru, Kenya, at the approximate position

17 0°21'33.77"S, 36°5'16.44"E located by using a hand held GPS. The site constitute the deepest

18 area in the central part of the lake (WLD, 1979) thus represented the sediment accumulation

19 bottom. A light weight sediment core sampler closing at both top and bottom ends of the

20 sampler tube was constructed especially for sampling in Lake Nakuru. The sampled core had

21 a diameter of 100 mm and was sliced at 5 mm resolution. Upon visual inspection of the

22 sediment matrix, the surface layers revealed blackish, fluffy layers with distinct smell of

23 decay of organic matter including bird fecal, the sediment consistency became more firm with

24 increasing depth and did not show any discrete horizons or layers. The sampling took place at

25 mid-day the 20th October 2001 followed by core slicing the same day. Slices were air dried

26 before transport. The season was dry and hot resulting in a maximum water depth of ~0.85 m

27 located at the sampling site. The lake had a concentrated smell of bird dropping and was at the

28 moment visited by a large amount of Lesser Flamingo. Two soil samples (15 · 15 · 15 cm)

29 were collected in an elevated grass land and forest area, respectively, approximately one km

30 west from the lake.

31 <u>Radiometry</u>

32 Atmospherically deposited ^{210}Pb (^{210}Pb$_{excess}$) was determined by subtracting the supported

33 ^{210}Pb (^{210}Pb$_{supported}$) from the total ^{210}Pb inventory (^{210}Pb$_{tot}$). It was assumed that the supported

34 ^{210}Pb formed through ^{226}Ra decay in the sediments were at steady state and no losses occurred

35 through radon emanation. In this case determination of ^{210}Pb$_{supported}$ was made from the lowest

36 obtained value of ^{210}Pb in the core. (Appelby and Oldfield, 1978)

37 Activity of ^{210}Pb$_{tot}$ was determined by measuring the α - emission from ^{210}Po → ^{206}Pb (stable)

38 according to Flynn (1968) and Appleby and Oldsfield (1978). Sediments of ~1 g were dried at

39 95°C for 48 h, homogenized and weighed. A well-known amount of a yield determinant

40 (about 0.1Bq ^{208}Po) and 30 ml *aqua regia* was added to the sample which were then reflux-

boiled over night followed by filtering. The fluid was evaporated to dry salt and re-dissolved
with 1 M HCl, repeated three times. 2 ml conc. HCl, 50 mg ascorbic acid and 5 ml H_2O was
added and the solution placed in a cell with a bottom mounted Ni plate. After 2 h at 65°C the
Ni-plate was removed, rinsed with water, ethanol and ammonia and dried for 1 h at 65°C.
Alpha spectrometry was done using Canberra PIPS-detectors. Activity of ^{208}Po and ^{210}Po was
corrected for decay according to equation [1] $A_t = A_0 \cdot e^{-k \cdot \Delta t}$, where
$k = \ln2 / t_{\frac{1}{2}}$ (^{208}Po $t_{\frac{1}{2}} = 1058$ d and ^{210}Po $t_{\frac{1}{2}} = 138$ d), Δt = the time from disequilibria
(deposition time) until the time for measurement. (Appelby and Oldfield, 1978; Henriksson et
al., 2011). Decay correction of ^{210}Pb between sampling and Po-separation was negligible due
to the short waiting time (< 2 months).

Sediment accumulation rates obtained from ^{210}Pb decay (^{210}Pb $t_{\frac{1}{2}} = 22.26$ years) were
acquired by plotting log A as a function of d and applying linear regression in the form
$\ln A_t = -k/\Delta t + \ln A_0$ (eq. [1]) where $\Delta t = (d \cdot r)$, d = depth (mm) or (g cm^{-2}) and r = linear
accumulation rate (mm y^{-1}) or mass accumulation rate (g cm^{-2} y^{-1}). (Bollhöfer et al., 1994)

Analysis of ^{137}Cs was performed by gamma spectrometry by recording γ radiation at 662 keV
directly from a weighed quantity of dried sediment.

Analysis of $^{239+240}Pu$ and ^{228}Th / ^{232}Th was done by α - spectrometry after chemical separation
from the bulk. According to Holm (1984), a weighed quantity of 2-3 g dried and
homogenized sediment was ashed in 550°C overnight. ^{242}Pu tracer as a yield tracer was added
and the sediment was dissolved in *aqua regia* overnight. The solution was evaporated and the
remaining salt dissolved in HCl, followed by filtration. The filtrate was precipitated as mixed
hydroxides by adding ammonia and then centrifuged. The supernatant was removed and the
precipitate was dissolved in 8M HNO_3 with an addition of some 100mg $NaNO_2$. The solution
passed through an ion exchange column absorbing Pu and Th where Th was eluted with 9M
HCl and Pu eluted with 9M HCl+ 0.1M NH_4I. Some tens of milligrams of Na_2SO_4 was added
to the Pu and Th eluates and then evaporated. The salt was dissolved in H_2SO_4 and pH
adjusted with NH_3/H_2SO_4 to pH 1.8 - 2.1. Electroplating of Pu and Th onto stainless steel
discs from the solution was done at an applied current of 1 A during 1 h. The steel plates were
rinsed in water, ammonia and acetone before being analyzed by alpha spectrometry for Pu and
Th-isotopes using Canberra PIPS detectors.

Determination of organic material

Organic material content in the dry sediments were determined by oxidation at 550°C during
24 hours. The results were calculated as ash weight / dry weight and presented as ash free dry
weight (%). (Bydén et al., 1996)

ICP-OES analysis

The elements Cd, Cr, Cu, Hg, Ni, P, Pb and Zn were analyzed with ICP. Dry sediment
samples were weighed, heated in concentrated HCl overnight, filtrated with paper filter
(Munktell no. 5) followed by cellulose filter (22.5 µm pore size) and analyzed on
an ICP-OES 3520B (ARL Instruments) calibrated with Atomic Spectral Standards (Analytical
Standards AB). Four sediment samples following the same procedure were also heated in

1 *aqua regia* and used to obtain a relative correction factor between the two methods. The

2 results in (ppm) were calculated from dry sediment weight and presented as an average for the

3 entire core 0 - 325 mm depth. Coefficient of variation, CV, from ICP-OES analysis was

4 expressed in (%).

5

6 **Results**

7 <u>^{210}Pb decay profile and sediment accumulation rates</u>

8 The activity of excess ^{210}Pb was plotted against sediment depth, see Figure 1. The resulting

9 profile showed that the activity near the surface was ~20 % lower than the maximum seen at a

10 depth of ~90 mm, hereafter the activity decreased exponentially with sediment depth. At the

11 depth of 322.5 mm the activity was 0.077 Bq g^{-1} and this value was used to determine the

12 sediment ^{210}Pb support level resulting from uranium series background. Linear regression of

13 data below 140 mm depth, see insert in Figure 1, resulted in k = -0.0247 (R^2 = 0.84) thus

14 calculations according to equation [1] resulted in a linear sediment accumulation rate of

15 1.3 mm y^{-1} (± 0.2 mm y^{-1}). The ^{210}Pb activity plotted against the mass depth is presented in

16 Figure 2. Linear regression of data > 2 g cm^{-2}, see insert in Figure 2, resulted in k = 1.1478

17 (R^2=0.85) thus the mass sediment accumulation rate was calculated by equation [1] to

18 0.027 g y^{-1} (± 0.004 g y^{-1}). Total inventory of ^{210}Pb in the surface soils were 0.104 Bq g^{-1} in

19 the savanna and 0.126 Bq g^{-1} in the forest. The excess ^{210}Pb in the upper 150 mm of the

20 sediment core accumulated to 0.138 Bq g^{-1}.

21 <u>Decay profiles of ^{137}Cs, $^{239+239+240}$Pu and ^{228}Th/^{232}Th</u>

22 The results from ^{137}Cs and $^{239+239+240}$Pu analysis did not show any clear trend between

23 15 - 280 mm depth, nor did the ^{228}Th/^{232}Th ratio in the analyzed interval of 15 – 100 mm

24 depth (Figures S4-S5).

25 <u>Profiles of sediment density, organic material and total Phosphorus</u>

26 Sediment dry mass relative to organic material and total Phosphorus content was plotted

27 against depth and presented in Figure 3. The result clearly showed that sediment density

28 increased with depth inversely proportional to the decrease of organic material content. The

29 concentration profile of total Phosphorous followed the trend of the organic material.

30 <u>Content of heavy metals</u>

31 The results from ICP measurement of heavy metal content in sediment are presented in

32 Table 1. For most metals the concentration showed insignificant variation with sediment

33 depth, thus presented as an average of 0 - 325 mm depth. However, notably lead

34 concentrations increase by some 10-20% below 150mm depth (Figure S7).

35 **Discussion**

36 <u>^{210}Pb decay profile and sediment accumulation rates</u>

²¹⁰Pb profiles with a decreased or flattening activity near the surface of the sediment have previously been reported (Donazzolo et al., 1982; Koide et al., 1973; Christensen and Chien, 1981) and ascribed to a physical or biological mixing zone. Considering that Lake Nakuru often have relatively strong afternoon winds, wave motion may likely reside in force through the shallow water column consequently moving particles. The wave motion occurs in a horizontal ellipse where the amplitude decline with depth by increased viscosity and friction, particularly as the motion enters the sediment. (Kundu, 1990). Vareschi (1982) however argued that wind-speed rarely was of a magnitude large enough to cause significant sediment resuspension. This must however be regarded in connection with the variable water depth. During low water levels resuspension should be more frequent at a given wind speed. (Vareschi, 1982)

The benthic zone in Lake Nakuru has been reported to be deficient in larger organisms that could possibly cause bio-turbation of the sediment. (Vareschi, 1978) Vivid microbial activity in the lake result in a highly oxidized potential close to the surface of the water column that sharply decrease with depth where large amounts of organic material including bird faeces cause anaerobic conditions near- and in the sediment. (Vareschi, 1978; Greichus et al., 1978) This is consistent with 1) observations made at the slicing of the sediment core where viscous organic material caused difficulty to define the water-sediment interface and 2) the resulting profiles of organic material and total Phosphorous seen in Figure 3.

It may therefore be expected that the resulting ²¹⁰Pb decay profile obtained from Lake Nakuru is a consequence of slow physical sediment mixing to an approximate depth of 90 mm. In addition, the difficulty in identifying the exact water-sediment interface opens for a possibility that the absolute level of 0 mm depth was determined with inaccuracy. Thus, to allow for tolerance in absolute sediment depth, it was decided to avoid the flattened decay profile around 90 mm depth and calculate the sediment accumulation rate below 140 mm depth where the ²¹⁰Pb decay profile demonstrated exponential decay. Assuming the depth of the mixing zone has been roughly constant with time the exponential decline in ²¹⁰Pb below the mixing zone is a measure of the sediment accumulation rate. Tolerance of the absolute sediment depth does not affect the calculated sediment accumulation rates because these are relative calculations. Due to the amphoteric nature of lead it may be anticipated that both stable lead and ²¹⁰Pb partly may exist as soluble forms. The integrated ²¹⁰Pb level of 4250 Bq/m^2 (equaling a steady state flux of 130 Bq per m^2 and year) is however within expected range or even a bit higher than what would be expected. Unfortunately published ²¹⁰Pb fluxes on the African continent are relatively rare so values to compare with are scarce but in general ²¹⁰Pb fluxes are proportional to the annual rain rate.

The sampling spot was chosen at the deepest central part of the lake. This spot is the most unlikely place for a mammal to visit, or, the flamingo to be standing because of the bird's limitation of standing in deep water, nor any other large bird. Furthermore, if hippopotamus had disturbed the sediment where the sediment core was obtained, there would indeed be no variation of ²¹⁰Pb decay with depth. The spot chosen for sampling most likely represent the best area for obtaining sediment cores, however it can still not be excluded to 100% certainty

1 that the sediment have been disturbed by any animal in recent history during abnormally low
2 water levels.

3 Sediment dry weight plotted against depth in Figure 3 demonstrate scattering of data points
4 which reflects the difference in wet volume of each slice generated during slicing. Ideally, the
5 profile should in general have an appearance of a smooth line with variations in certain
6 chronological layers of different sediment density

7

8 <u>Determination of ground content of ^{210}Pb</u>

9 Organic surface soils at non-erosion locations are considered to contain excess ^{210}Pb due to
10 integrated accumulation from precipitation. [Bro11, Per11] As expected, the excess ^{210}Pb in
11 the upper 150 mm of the sediment was higher than the control samples obtained from the
12 surface soils in the forest and savannah, however, the soil sample from the forest may show
13 too high activity because the bottom 30 mm of the sampled cube was composed of dense
14 mineral soil rather than organic soil. Mineral soil could possibly contain support ^{210}Pb due to
15 slow diffusion of ^{222}Rn. (Brown et al., 2011; Persson and Holm, 2011). Assuming a supported
16 ^{226}Ra of about 50 mBq/g and a unit density the areal inventory of excess ^{210}Pb at the two
17 terrestrial sites becomes 8100 and 11400 Bq/m^2 respectively, thus very high compared to the
18 world average. The dense mineral soil appeared to be originating from volcanic material, thus
19 the lake and its wide stretched flat surroundings likely constitute one large pan. The terrestrial
20 soil sample should probably be better represented if collected at a site further away from the
21 lake, at a slightly higher altitude and with deeper content of organic type of soil.

22

23 <u>^{137}Cs, $^{239+240}$Pb and ^{228}Th/^{232}Th</u>

24 The absence of bomb ^{137}Cs and $^{239+240}$Pb peaks in the sediment profile, as well as an absence
25 of a decreasing decay profile of ^{228}Th/^{232}Th in the upper 100 mm is a likely consequence of
26 slow physical sediment mixing to an approximate depth of 90 mm. This may indicate that
27 either the sediments are mixed or that transport of particle reactive material (where ^{228}Th and
28 Pu-isotopes are attached to) occur with a delay and at a slow rate so that the time lag between
29 deposition in the catchment area and the transport + deposition in the lake sediments takes in
30 the order of years.

31 Levels of radiocesium deposition in the equatorial regions from global fallout was very low
32 (UNSCEAR) and other sources are in practice absent at these latitudes. It is well-known that
33 clay minerals, *e.g.* Illite (Comans et al., 1989), are the main trap for dissolved cesium in fresh
34 and marine waters. Although it has been reported that anoxic conditions in the lake water are
35 unlikely due to daily mixing caused by wind (Vareschi, 1982), the high organic load most
36 likely cause the interstitial water in the sediments to become anoxic with high NH_4^+
37 concentrations as a consequence. Temporarily bound radiocesium thus probably experience
38 extensive ion exchange reactions and are becoming solubilized shortly after burial, especially
39 when sediments are poor in clay minerals. The integrated ^{137}Cs of about 850 Bq/m^2 is roughly

what is expected at these latitudes of the deposited from fallout. Similarly the Pu may be released due partly to carbonate complexation and partly due to colloidal formation of organic material in the sediment deposits (Cleveland et.al., 1983; Sanchez et.al., 1986). It is however interesting that the integrated $^{239+240}$Pu of 40 Bq/m^2 is nearly twice that is expected at these latitudes (UNSCEAR, 1980) which indicates that the sediments is a main reservoir for deposited Pu in the lake. Ratios ^{238}Pu/$^{239+240}$Pu were all lower than 3% showing that the contribution from the SNAP-9A event in 1965 was negligible as expected.

ICP measurements and heavy metal contents

The elements Cd and Zn generate a larger error in ICP-OES analysis than the other elements due to closeness of atomic spectral lines. The results from heavy metal analysis of the sediment show that there is no significant change of concentration with depth except for lead which show concentrations by some 10-20% higher below 150mm depth (Figure S7). In general the concentrations are rather high for a lake, however alkaline salt lakes in volcanic bedrock may well have high natural concentrations of heavy metals. (Loberg, 1999) The only metal that impose a noteworthy difference in comparison to previous measurements is Cd which in our study was higher, 4 ppm compared to 0.27-0.48 reported by Ochieng et al. (2007) and Greichus et al. (1978).

Summary

In summary, the conditions in Lake Nakuru of 1) shallow water body 2) frequent afternoon winds resulting in motion of the water column and loose surface sediments and 3) a viscous water-sediment transition zone introducing tolerance in determination of absolute sediment depth eliminated the possibility to obtain accurate sediment chronology in a recent time scale using ^{210}Pb. Instead, by calculation of data below the mixing zone, sediment accumulation rates were successfully obtained. In general, the sediments contained high amounts of heavy metals. The integrated levels of artificial radioisotopes and the natural ^{210}Pb are at, or somewhat above, what would be expected which shows that the sediments themselves are the main reservoir for deposited radioisotopes in spite of the very different water chemistry.
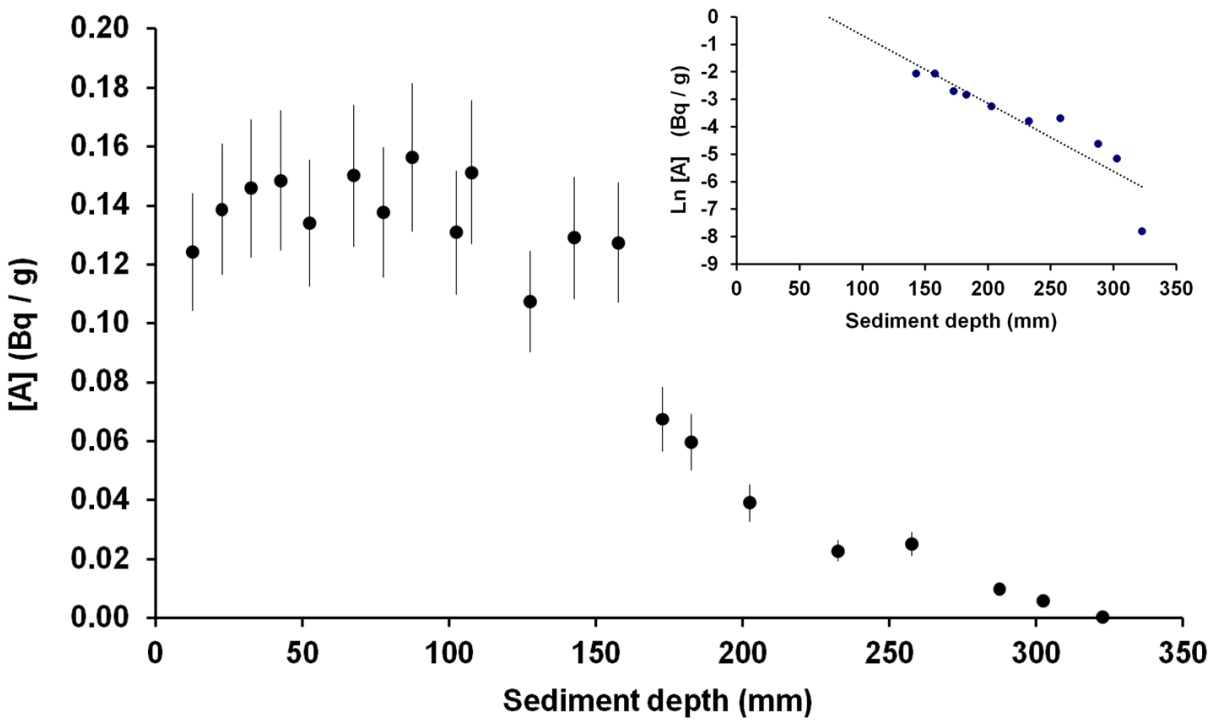
Figures and Table

Figure 1 ^{210}Pb decay (± 16%) profile in sediment from Lake Nakuru. The linear

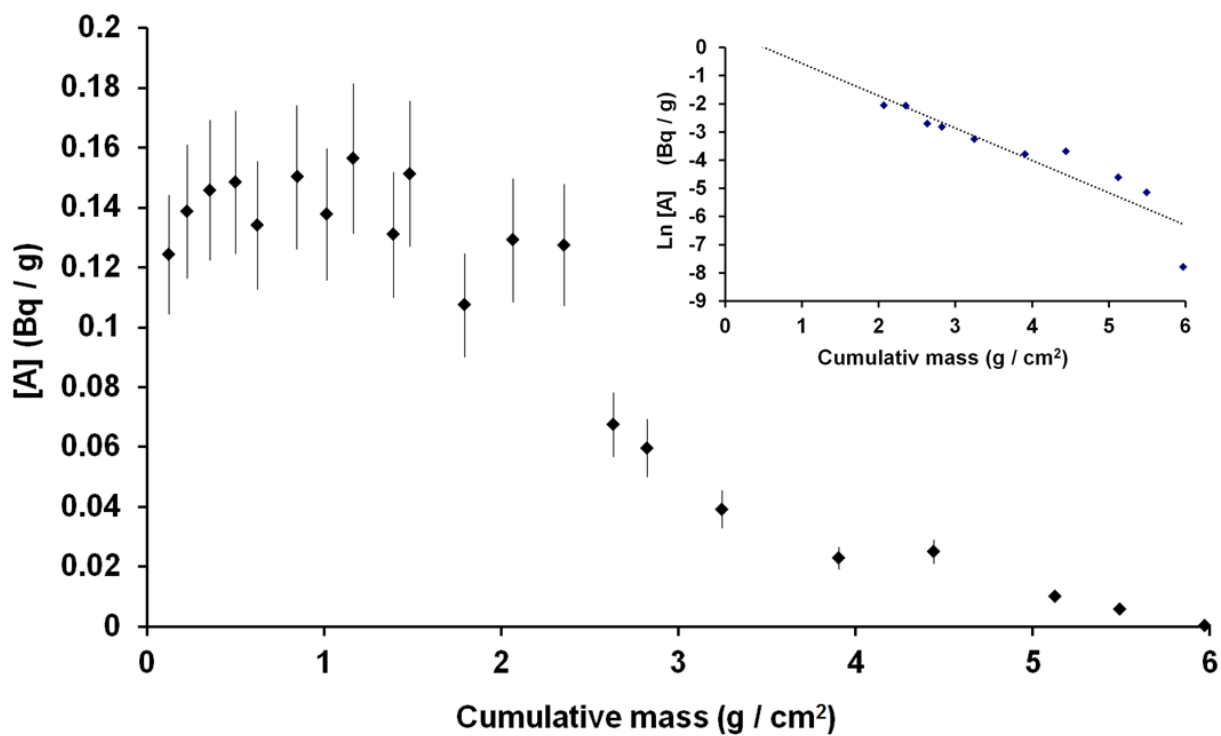sediment accumulation rate 1.3 mm y^{-1} was calculated from linear regression (insert).

Figure 2   Mass depth of ^{210}Pb decay (± 16%) in sediments from Lake Nakuru. The sediment mass accumulation rate 0.027 g cm^{-2} y^{-1} was calculated from linear regression (insert).
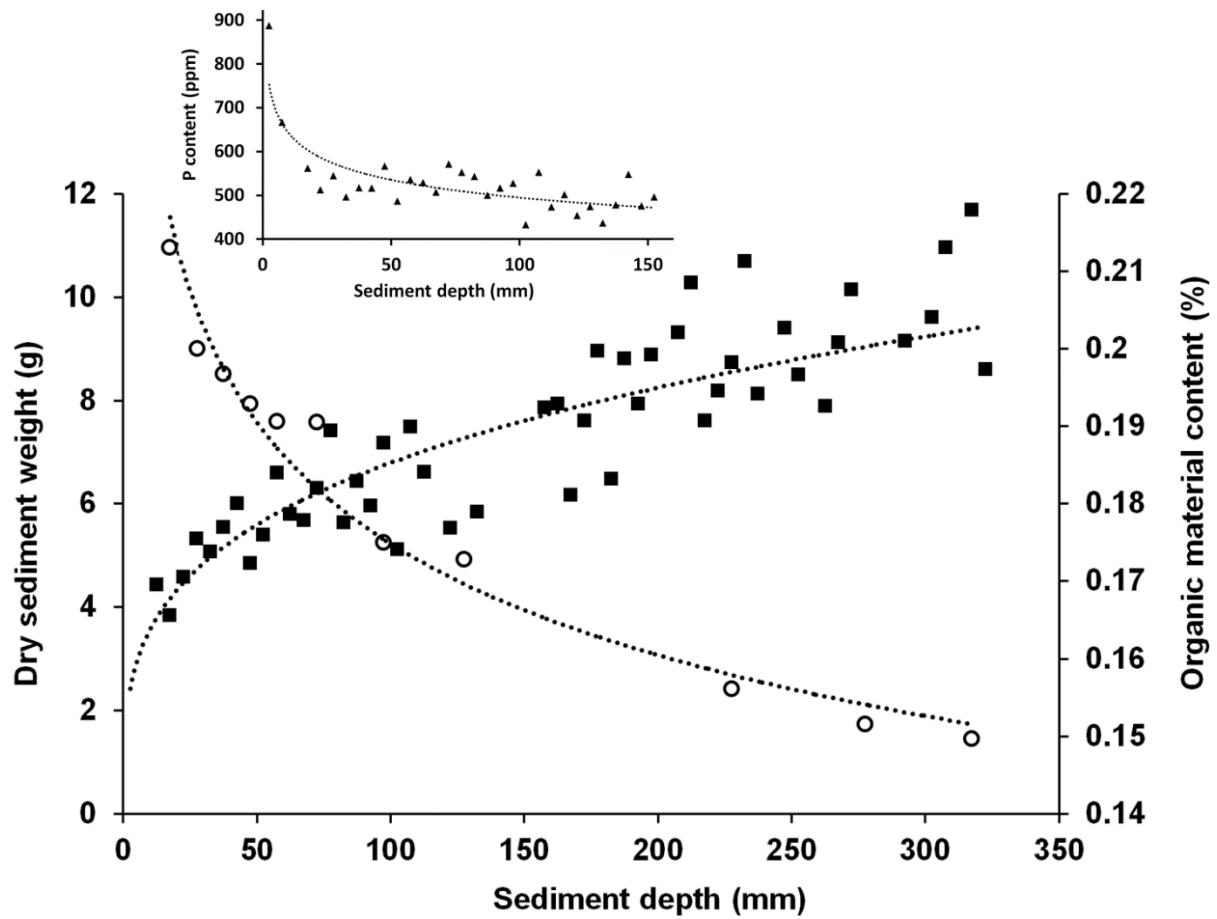
1

2

3 **Figure 3**   Graph showing sediment dry mass (left axis) increasing with depth,
4 correspondingly, the organic material (right axis) decreases with depth in accordance with
5 total Phosphorus content (insert). The trends are highlighted by power regression lines
6 (dashed lines), serving as guides for the eye.

7

1 **Table 1** Heavy metal content in lake sediment calculated from dry weight in ppm (µg/g).
2 Statistical error presented as coefficient of variation, CV (%). The results are compared to
3 three previous studies.

	Cd	Cr	Cu	Hg	Ni	Pb	Zn
This study	4	10	8	<1	10	30	142
CV (%)	46	32	41	3	20	19	8
Ochieng et al., 2007 *	0.48	1.95	2.89		15.58	14.36	154.1
(±ppm)	0.10	0.075	0.06		0.31	0.75	15.3
Nelson et al., 1998 **		67	24			22	147
Range***		10-280	5-95			4-100	44-630
Greichus et al., 1978	0.27		6.2	<0.5		34	140

4 * Average from 3 sample sites. ** Average from 11 samples sites. ***The concentration range of the
5 11 sampling sites.

6

7

8 **Table 2** Fall out of radioactive isotopes (Bq/m^2) in Lake Nakuru in comparison to global
9 fallout in the southern tempered zone (UNSCEAR, 1980).

	^{137}Cs	$^{239+240}$Pu	^{210}Pb
Lake Nakuru sediments	847	40	4250
Global fallout south temp. zone	1420	16	

10

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17

1 **Supplementary information**
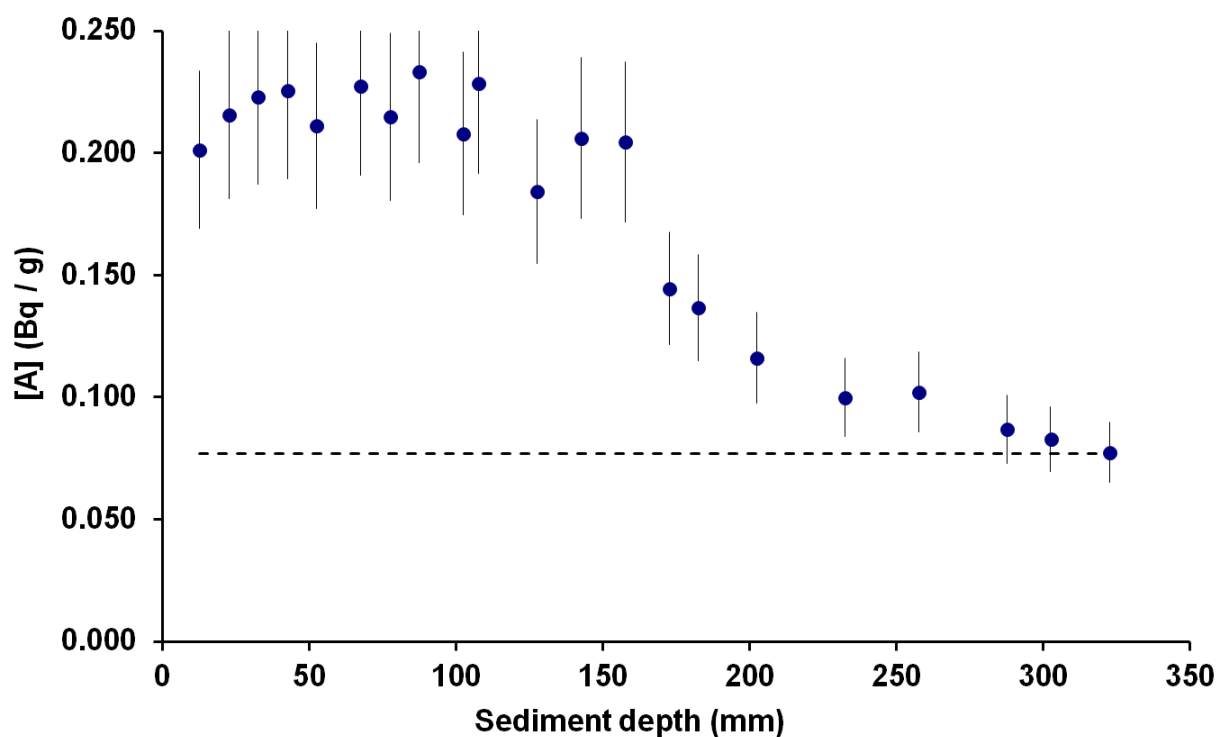
2

3 <u>**Table of content**</u>

12

1

2 **Figure S1** Total inventory ^{210}Pb decay profile from sediment in Lake Nakuru. The dashed
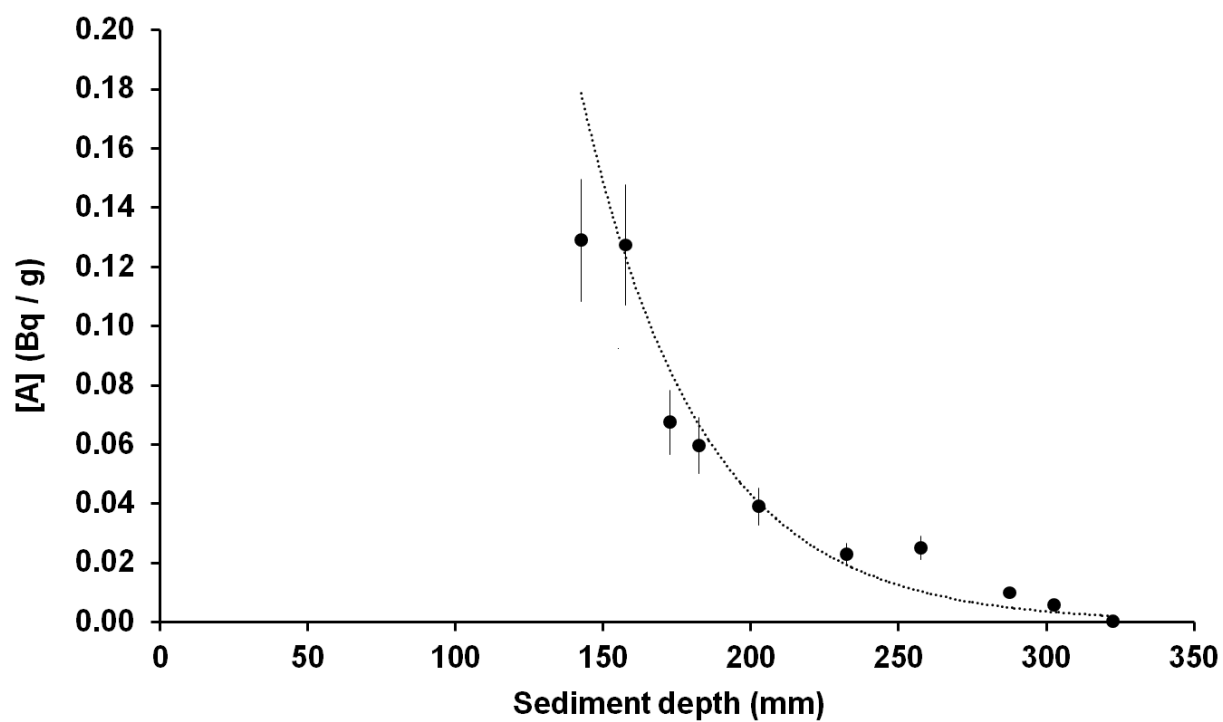3 line indicates the supported level of ^{210}Pb in the sediments. Error estimated to ± 16%.

4

1

Figure S2   Sediment profile of ^{210}Pb below ≥142.5 mm depth showing a power regression
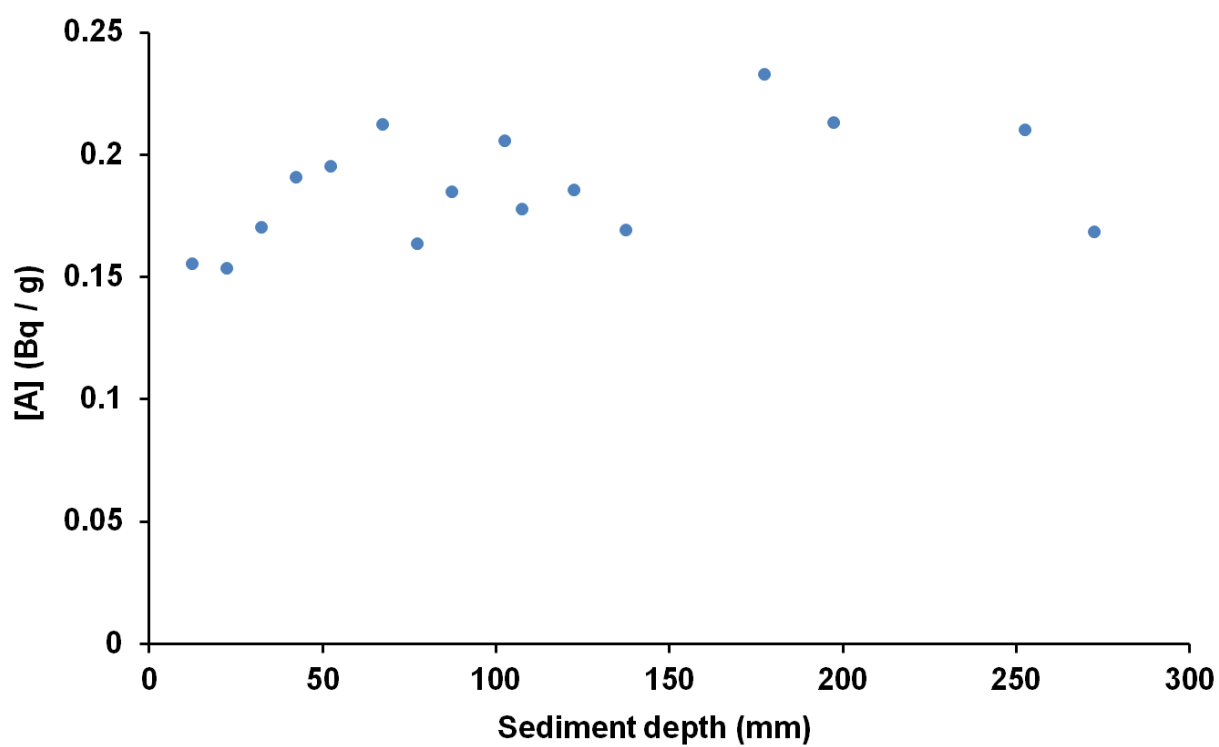line y = 6.07e$^{-0.025x}$ with a fit of R^2 = 0.84.

1

2   **Figure S3**   Sediment profile of ^{226}Ra, the average activity was 0.19 Bq g^{-1}.

3

1
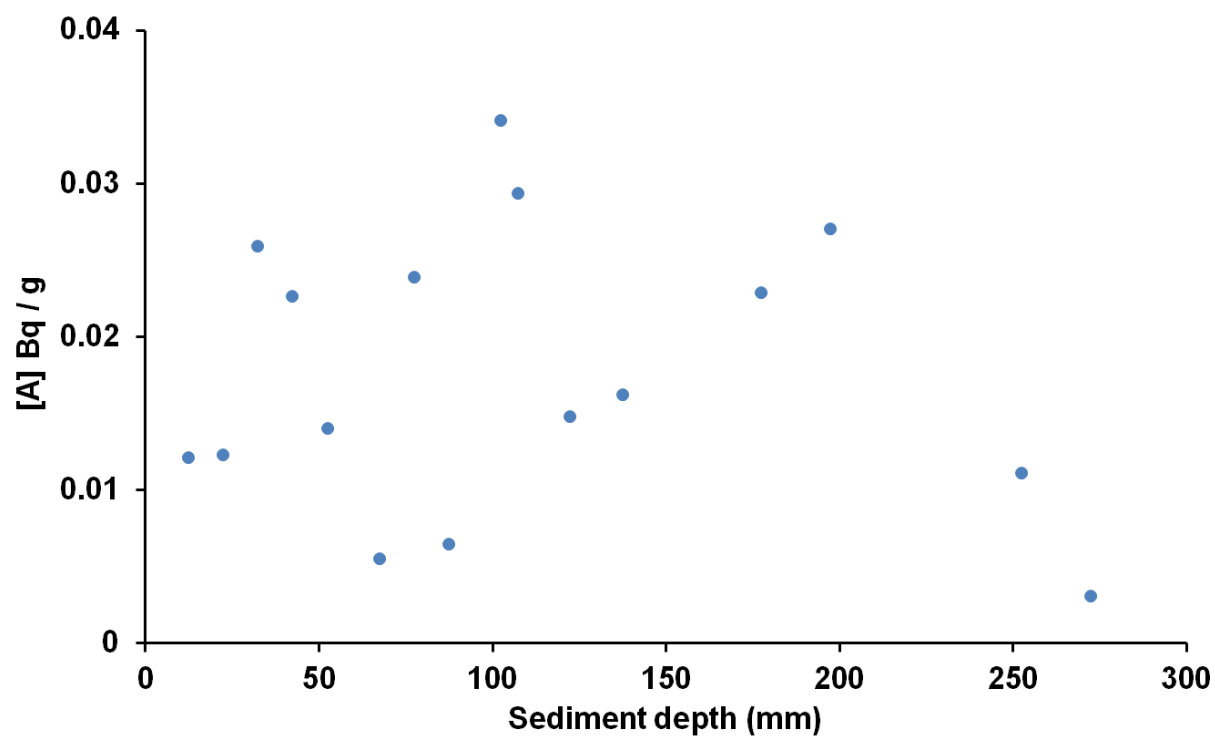
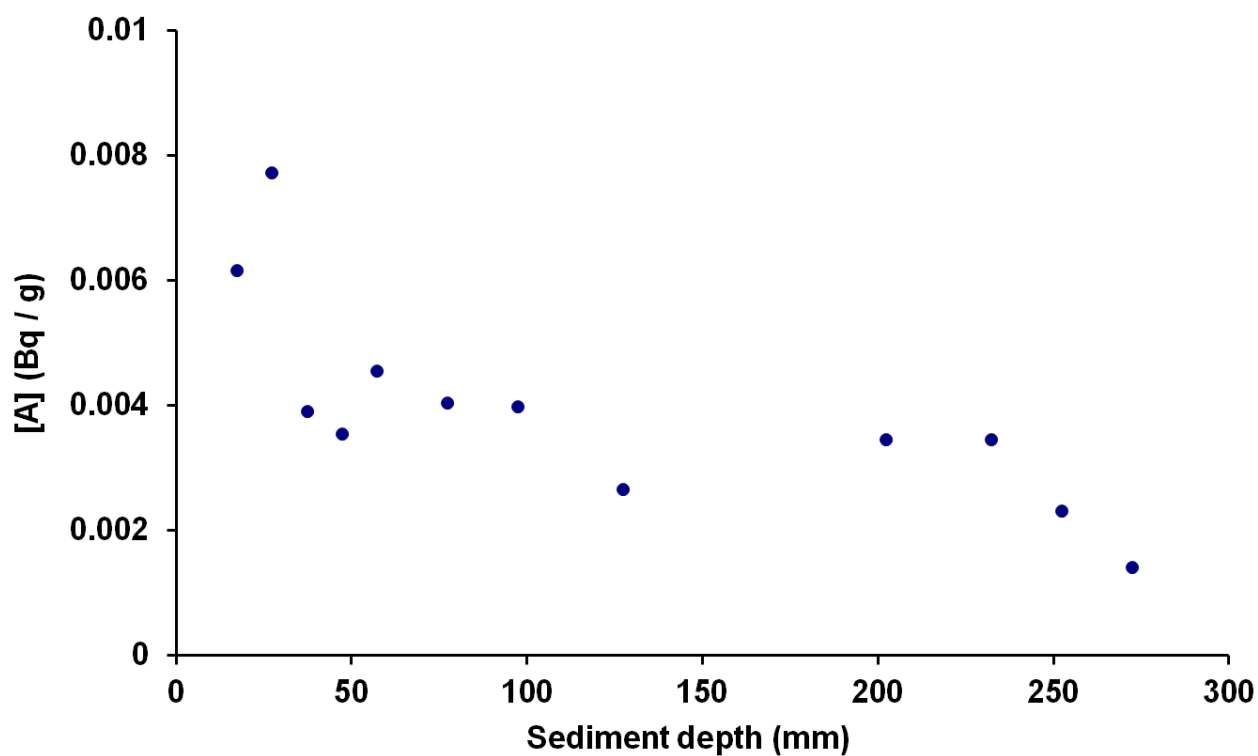2   **Figure S4**   Sediment profile of ^{137}Cs. Scattered concentrations indicates mixing of
3   sediments.

4

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Figure S5   Sediment profile of $^{239+240}$Pu. The higher concentration at the surface may likely
be a consequence of a chemical processes, for example flux of Pu bound to phosphorus
precipitate or organic material. The wave motion mixing of sediment to a depth of ~90 mm
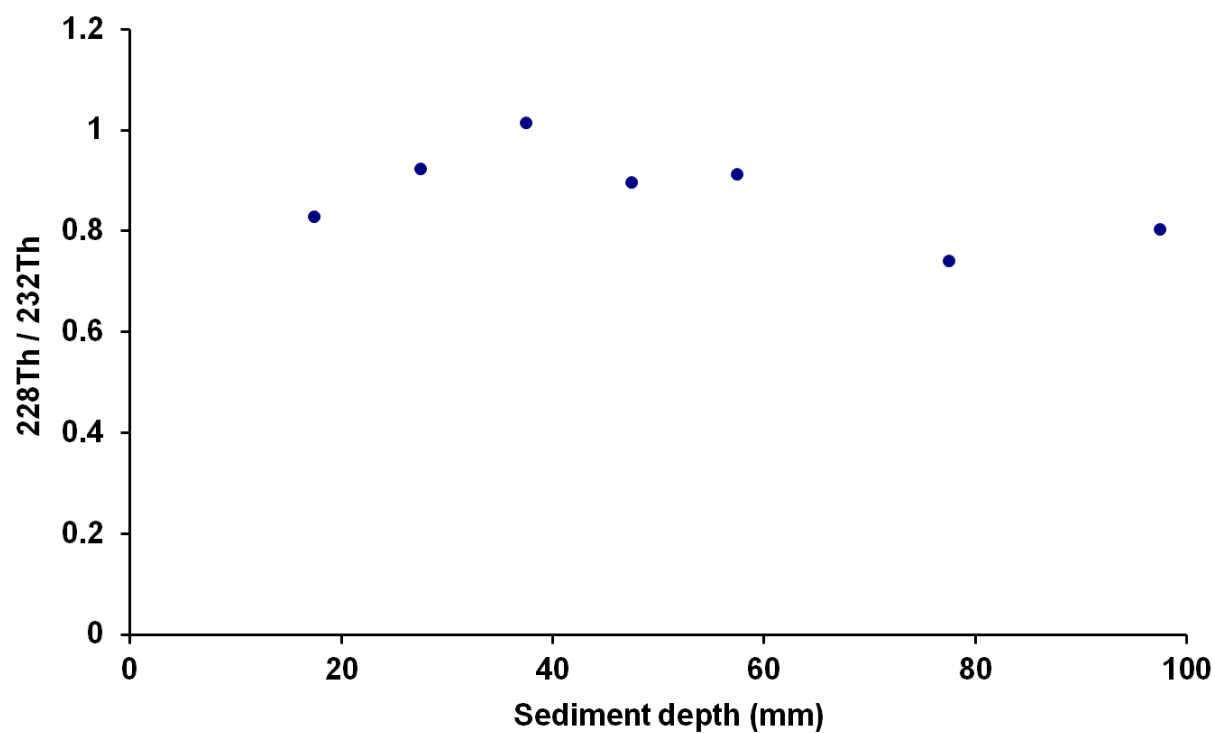would not allow for a chronological peak.

6

1

2 **Figure S6**   Sediment profile of ^{228}Th / ^{232}Th. In undisturbed sediments the fraction
3 commonly reaches between 0.5 and 10 in an exponentially decreasing profile.
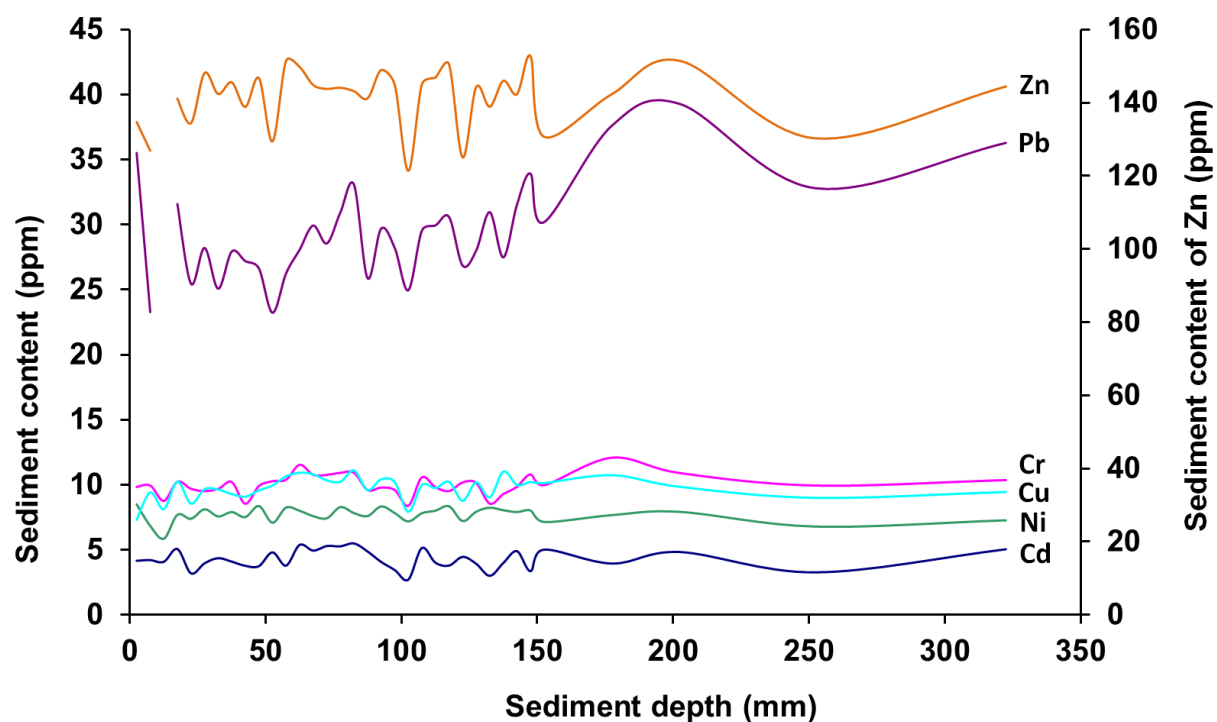
4

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2 **Figure S7**   Sediment core profiles of heavy metal content demonstrating insignificant
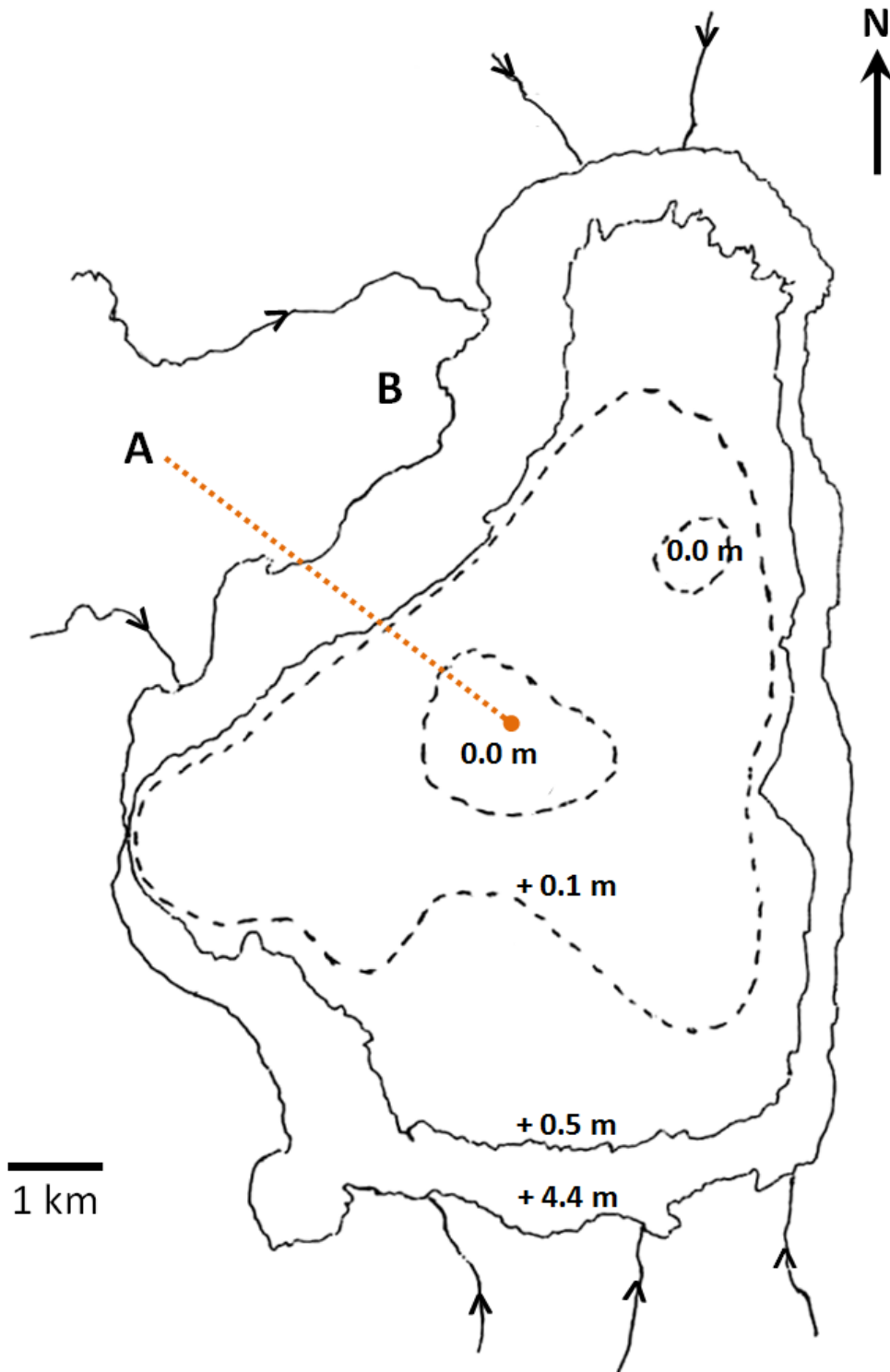3 concentration changes with depth within errors. Average values are presented in Table 1.

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2 **Figure S8**   Illustration of a bathymetric map of Lake Nakuru with isopleths at various
3 heights of the water column. (WLD, 1979) The lake surface level exhibit large seasonal
4 variations. The sediment core was sampled from A (approx. location
5 0°21'33.77"S, 36°5'16.44"E) that represent the sediment accumulation bottom of the lake.
6 Ground reference samples was taken from B (approx. location 0°19'47.27"S, 36°4'12.68"E)
7 located above the highest lake level.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Contribution

Paper: SVENGREN et al

Henrik Svengren; main author. Performed sampling, sample analysis, raw data processing, main authoring of manuscript.

Pär Roos; supervising and in-part-performing the practical part of sample analysis with Henrik Svengren in laboratory. Calculations. Co-authoring manuscript.

Daniel Koros; supervising sampling in situ, in Lake Nakuru, Kenya, co-operating sampling process in lake. Co-authoring manuscript.

Gunnar Svensson; main professor in the research project, co-authoring, reviewing of manuscript.

Cover Letter

Paper: SVENGREN et al

This paper presents unique sediment data of one of the world´s most popular Flamingo Lakes (BBC, National Geograpic broadcasts) as well as one of the main National Park in Kenya regarding visiting numbers per year - but most of all an outstanding site for study of environmental chemistry as the surrounding landscape is densely inhabited with a human population situated in a water basin without drainage; all ends up in the salt water Lake Nakuru where only evaporation allows water to escape. The sediment collects historical events taken place in this special catchment basin. The unique data set is until now never published elswhere and no comparable research data has ever been made here. The paper represents a historical mark in the research history of Lake Nakuru and shows a method of performing sediment dating in a shallow salt lake, thus an excellent paper for contemporary research to relate to.

Yours sincerely

Henrik Svengren, corresponding author

Highlights

Paper: SVENGREN et al

- Sediment sampling in a shallow salt water lake possible by using a core sampler
- Sediment dating using radio isotopes requires analysis results in
- Accumulation rates determined by sediment core in Flamingo habitat human population
- Lake Nakuru Kenya offers inventories heavy metal and core profiles of organic material decay
- Lead Pb 210 decay method resolution at deepest point catchment area basin