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Using multi-proxy analysis to determine the long-term impacts of catchment dynamics on water reservoirs - A case from a tropical reservoir (Ruiru Basin Kenya)

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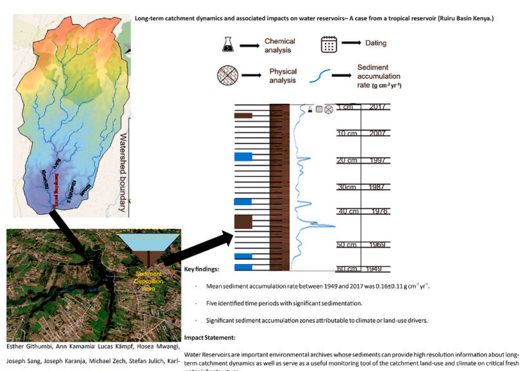
HIGHLIGHTS

- Water reservoirs as 20th century environmental archives.
- Multiproxy sediment characterization documents catchment dynamics.
- Six significant sediment accumulation periods identified from 1949 to 2017.
- Attribution of sedimentation layers to land-use change and weather events.
- Identification of climate and anthropogenic drivers of erosion through sedimentation layers.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally, siltation of water reservoirs is a major risk and cost to the provision of fresh water. Therefore, managing reservoir sedimentation is a significant task for water management agencies. In Kenya, the Ruiru water reservoir,

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one of four water reservoirs supplying Nairobi with drinking water has experienced a significant loss of volume since construction in 1949. However, there have been no studies characterizing the long-term catchment dynamics such as erosion, sedimentation and accumulation in the reservoir. A detailed understanding of the sediment dynamics such as identification of sediment source area; processes driving soil erosion in the catchment and accumulation in the reservoir, and identification of flood layers are necessary for the reservoir and landscape management. The accumulated sediment has not been characterized; therefore, long-term land-use and climate change impacts on the catchment on the reservoir are not documented. The study aims to identify the historical land use and climate events in the catchment impacting the reservoir through a multiproxy sediment characterization of the sediment accumulating in the Ruiru reservoir. An undisturbed 1-m sediment core retrieved in 2017 from Ruiru Reservoir was dated using ^{210}Pb and ^{137}Cs and particle size distribution and chemical element profiles analyzed. The accumulated sediment is a predominantly fine-grained red silt, with a particle size end-member analysis identifying four possible sources or processes of sediment accumulation. The multi-proxy analysis reveals six periods of significant accumulation, 1949, 1963/64, 1974/75, 1982/83, 1997/98 and 2013/14. The peaks coincide with high rainfall events and two are attributed to significant land-use changes in the catchment. The study identifies the catchment dynamics with a significant sediment input into the reservoir. This highlights the importance of reservoirs as environmental archives documenting 20th century land –use and climate events while providing a long-term perspective for management of critical water infrastructure.

1. Introduction

The conversion of natural landscapes into predominantly agricultural areas and settlements is a global trend (Foley et al., 2005). This change, driven by population growth and economic development, has altered ecosystems, affected biodiversity, modified hydrological processes and affected climate patterns (e.g. Lambin et al., 2001; Foley et al., 2005). Large-scale land-cover conversion has resulted in changes in nutrient cycling, soil erosion, and water availability, affecting both terrestrial and aquatic ecosystems (Bullock et al., 2021). Loss of forests has led to severe consequences such as habitat loss and fragmentation, disrupting ecosystem services. Increased logging has caused changes in wind patterns, albedo and water conservation capacity (Laurance, 2004; Nakamura et al., 2017). Reduction of natural land-cover (for example through conversion into roads and buildings) has increased the extent of the impervious surfaces which has led to low infiltration rates, resulting to high run-off causing changes in hydrological flow patterns in watersheds (Kamamia et al., 2019). Worse still, such land-use/land-cover (LULC) shifts have increased vulnerability of catchments to impacts of global warming such as floods and droughts.

East Africa, like most of the world, has not been an exception to these changes. Bullock et al. (2021) indicated a notable increase in cropland (35 %) and settlement (43 %) over a three-decade period (1988–2017). While an increase in settlement in most East African countries was from wooded grasslands and cropland, in Kenya the change was attributed to deforestation of dense forests.

The dramatic land-use change in East Africa is linked to increasing soil erosion and associated land degradation (Borrelli et al., 2017; Pimentel et al., 1995; Vanmaercke et al., 2014). Moreover, soil erosion has led to increasing sediment loads in many rivers (Dunne, 1979), lakes and reservoirs (Hunink et al., 2013; Stoof-Leichsenring et al., 2011; Vanmaercke et al., 2014; Vogl et al., 2017; Wooldridge, 1984). This has a negative feedback on their capacity and functionality, posing challenges to their long-term viability whether their utility is fresh water supply, agricultural productivity or hydropower energy generation because the sedimentation reduces the storage capacity of reservoirs (Dutta, 2016; Hunink et al., 2013; Schleiss et al., 2016; Wang and Hu, 2009).

Although the detrimental impact of soil erosion in tropical Africa has been recognized for several decades (Lal, 1985; Ngecu and Ichang'i, 1999; Zöbisch et al., 1995), the number of studies on long-term soil erosion and sediment yield dynamics within a catchment are limited and the results show a high range of variability and uncertainty (Vanmaercke et al., 2014). Several studies have attempted to determine erosion rates at plot and river basin scales (Mutema et al., 2016; Vanmaercke et al., 2014) or sediment yield in natural lakes and reservoirs (Stoof-Leichsenring et al., 2011). Data sources providing a long temporal perspective are unavailable and thus water reservoirs are important environmental archives. Sediment cores from lakes and wetlands have been used for decades to document environmental change. With the development of radiometric dating techniques that allow dating of younger material (>250 years); the techniques can now be applied to younger records with a view to identify not only catchment dynamics but also as a management tool through the monitoring of sedimentation in relation to catchment climate and land-use. The lack of catchment scale long-term land-use and climate data across the developing world can be approached though the utilization of water reservoirs which act as environmental archives.

Identifying the sediment source area, understanding the terrestrial processes that lead to sediment mobilization, the transport pathways of sediment and utilizing deposited sediment as a proxy for terrestrial processes can provide valuable insights into the dynamics of LULC change and erosion within the catchment area (Collins et al., 2020). In contrast to rivers, sediments of standing water bodies (lakes, reservoirs) act as traps for materials that originate from erosion in the watershed (Fryirs, 2013) and, hence, provide continuous records of catchment processes (Foster and Walling, 1994; Kunz et al., 2011).

Reservoir sediments have been used to reconstruct past erosion and related sediment yields in different parts of the world (Ben Slimane et al., 2013; Foster et al., 2007; Foster and Walling, 1994; Pittam et al., 2009; Snyder et al., 2006). In the East Africa region, sediments of reservoirs in Kenya have been explored by acoustic surveys to assess total sediment yields over the entire reservoir lifetime (Hunink et al., 2013; Maloi et al., 2016; Sang et al., 2017; Wooldridge, 1984). However, so far, without resolving temporal variability and deciphering sediment source areas.

Palaeoecological techniques are crucial for studying long-term ecosystem changes through the analysis of environmental archives like sediment and ice cores (Anderson et al., 2006; Froyd and Willis, 2008). Constructed reservoirs offer a unique advantage as their known accumulation start date and orderly sediment deposition allow for precise analysis of past environmental conditions (Amasi et al., 2021; Kondolf et al., 2014; Navas et al., 2009). Sediment cores, collected using specialized corers from areas of maximum accumulation, are carefully processed to examine their chemical, physical, and biological properties, including microfossils (Lotter et al., 1997; Wright, 1991). Continuous ^{210}Pb radiometric dating to develop an age-depth model, enables temporal interpretation of changes and comparison with climatic data and historical land use (Brenner and Kenney, 2015; Tylmann et al., 2016). By analyzing multiple properties—such as particle size, organic carbon, and elemental profiles—within the same sample, researchers gain a comprehensive understanding of the processes influencing ecosystem changes over time (Kunz et al., 2011; Sedláček et al., 2013; Stinchcomb et al., 2014).

The ^{210}Pb dating method, introduced by Goldberg in 1963 and refined over subsequent decades, relies on understanding ^{210}Pb within the ^{238}U decay series, where ^{210}Pb is produced from the decay of ^{222}Rn gas and deposited on Earth's surface through rainfall and dry fallout. In wetland sediments, this "unsupported" 210Pb is distinguished from "supported" ^{210}Pb, which originates from the decay of ^{226}Ra within the sediments. Dating models use only the unsupported fraction to determine ages, making this distinction crucial. With a half-life of 22.26 years, ^{210}Pb allows for the creation of continuous age-depth profiles spanning roughly the last 100 years, aligning with the era of profound human impact on ecosystems globally, making it a vital tool for examining recent environmental changes (Brenner and Kenney, 2015; Goldberg, 1963). The geophysical properties such as the grain size distribution along the core provide valuable information of the sediment transport processes through time. Different grain sizes have varying transport and deposition potential, and their distribution in the sediment core indicates the dominant transport mechanism. Grainsize is linked to velocity flow of water and maximum grainsize can reflect maximum velocity enabling identification of flood layers (Arnaud et al., 2016). The process of tracking sediments from the different source areas to a sink has been applied to different ecosystems, including estuaries (Faseyi et al., 2022), urban reservoirs (Voli et al., 2013; Walling et al., 2001), lakes (Ahmady-Birgani et al., 2018), marine ecosystems (Darby et al., 2015; de Mahiques et al., 2017) but is rather novel within the Kenyan context.

Analyzing the geochemical properties of the reservoir sediment such as elemental and biomarker composition should offer insights into the sediments (Romans et al., 2016; Smith and Blake, 2014; Wynants et al., 2020). Deposition layers identified by grain size and sedimentation rate can be linked to geochemical elements. This would allow the differentiation of the driving processes e.g. between land-use driven deposition layers and rainfall driven deposition layers. Variation in carbon-nitrogen (C/N) ratios within sediment cores have been utilized to determine historical organic matter changes and source areas. For example increasing C/N ratios as an indicator of organic matter source has been observed in lake sediments coinciding with timing of major land-use activities such as deforestation (Kaushal and Binford, 1999). Increases in C/N ratio indicates an increase in terrestrial organic matter while decreases in C/N ratios indicate increase in algal organic matter (Mekonnen et al., 2023; Meyers and Ishiwatari, 1993; Meyers and Lallier-Vergès, 1999).

The presented study focuses on the Ruiru Reservoir and its catchment in Kenya, East Africa where remote sensing and GIS analysis reveal a change in land cover from forests, grasslands, and shrubland to settlements and agriculture (Waithaka et al., 2020). Soil erosion within the catchment into the Ruiru River and its tributaries and finally to the reservoir is primarily driven by water.

Siltation has significantly reduced the Ruiru Reservoir volume by 14 % between time of construction in 1949 and the mid-2010s, and successions of basin-wide light-colored layers indicative of Fe-rich soil material have been observed (Sang et al., 2017). This layering suggests that sedimentation events coincide with pulses, such as during the onset of rainfall events. Within the Ruiru catchment, which is typified by a steep topography; conversion of natural ground cover to agriculture (annual and perennial cropping) and settlements has been identified as one of the main drivers of soil erosion (ESC, 2016; Maloi et al., 2016; Kamamia et al., 2021). Sedimentation into the reservoir occurs both continuously and as episodic pulses during events in the landscape such as heavy rainfall events. Erosion intensity within the catchment varies with LULC and directly affects the sediment contribution into the reservoir.

To address and mitigate these effects of the changing land-use, sustainable land-use planning and conservation efforts are crucial. Understanding the erosion and sedimentation dynamics is necessary for similar water reservoirs undergoing significant loss of volume at a time when there is need to consider the management and construction of similar critical infrastructural projects.

In the context of global environmental change and increasing demands on water resources (Gleick, 2000; Vörösmarty et al., 2000), understanding the sedimentation history of reservoirs is crucial for sustainable management and ecological health. Reservoirs are key components of water infrastructure, providing essential services such as water supply, flood control, and hydroelectric power. This study, offers a detailed investigation into the sedimentation patterns and processes over time in Ruiru Reservoir. By employing multiple analytical techniques, we aim to uncover the historical anthropogenic and environmental factors driving sedimentation. Our findings provide valuable insights for international stakeholders on how to identify and mitigate sediment-related issues and enhance the resilience of water resources in the face of climate change and anthropogenic pressures. The sediment core analysis approach is highly appropriate for identifying catchment dynamics, particularly in small catchments, where erosion, transport, and sedimentation processes are easier to analyze. This method is effective when detailed prior information about the catchment is lacking. For example, in the Ruiru reservoir, with a small catchment area of 51 km^2 and a varied elevation range, the sediment core approach has successfully been used to assess erosion and sediment deposition over time.

Given the lack of historical environmental and land-use data within the Ruiru watershed; the study develops the first reconstruction of the sediment deposition pattern in the Ruiru Reservoir since its construction 1949 by analyzing the geophysical and geochemical parameters of the sediment core collected from the reservoir. Two main hypotheses were tested, i.) Sediment accumulation rate has intensified over time and ii.) Periods of high sedimentation are observable and have been the main contribution to significant erosion and sedimentation into the reservoir. The utility of water reservoirs as sources of archives environmental change are highlighted.

2. Study area, materials and methods

2.1. Study area

The Ruiru Reservoir catchment covers an area of 51 km^2 (Fig. 1, details of SWAT methodology in supplementary file S5) from the Uplands area, adjacent to the Rift Valley faults, to the reservoir. The catchment elevation ranges between 1940 and 2434 m above sea level (asl) with higher elevations to the west and lower elevations to the east (Fig. 1). Ruiru reservoir construction began in 1936 and was commissioned for use in 1949. According to the FAO AQUASTATS the Ruiru reservoir had a pre-impoundment capacity of 2.98 m^3 which had decreased to 2.56m^3 and a reservoir area of 0.4 km^2 then 0.36 km^2 in 2015. The reservoir area is ~0.6 % of the catchment area. A bathymetric survey carried out in 2015 found water depth in the Ruiru reservoir ranged from 0 to 20 m while the sediment depth ranged from 0 to 2.4 m (Maloi et al., 2016; Sang et al., 2017). In 2017, during coring of the RU 12–1, the water level in the dam ranged between 8 m and 16 m with the lower levels along the tributary arms and the deepest part at the center of the reservoir.

The primary water source feeding the reservoir is the River Ruiru originating from the Kikuyu escarpment. According to the Köppen-Geiger climate classification the Ruiru catchment falls within the subtropical highland climate (Beck et al., 2023). The region experiences an average annual rainfall of 1300–1500 mm. The long rainy season occurs between March and May, while the short rainy season is from October to December. The monthly average temperature ranges between 13.0 and 24.9 °C (Nyakundi et al., 2015). The local climate where the reservoir is located is cooler with a mean annual temperature of 18 ± 0.8 °C. Days are much warmer than nights with diurnal temperature ranges of 12 ± 0.5 °C. Between 1901 and 2022 total annual rainfall has ranged between 500 and 1480 mm with an average of 911 ± 218 mm (Fig. 1). The dominant soil types are Nitisols (well drained, reddish to dark brown in

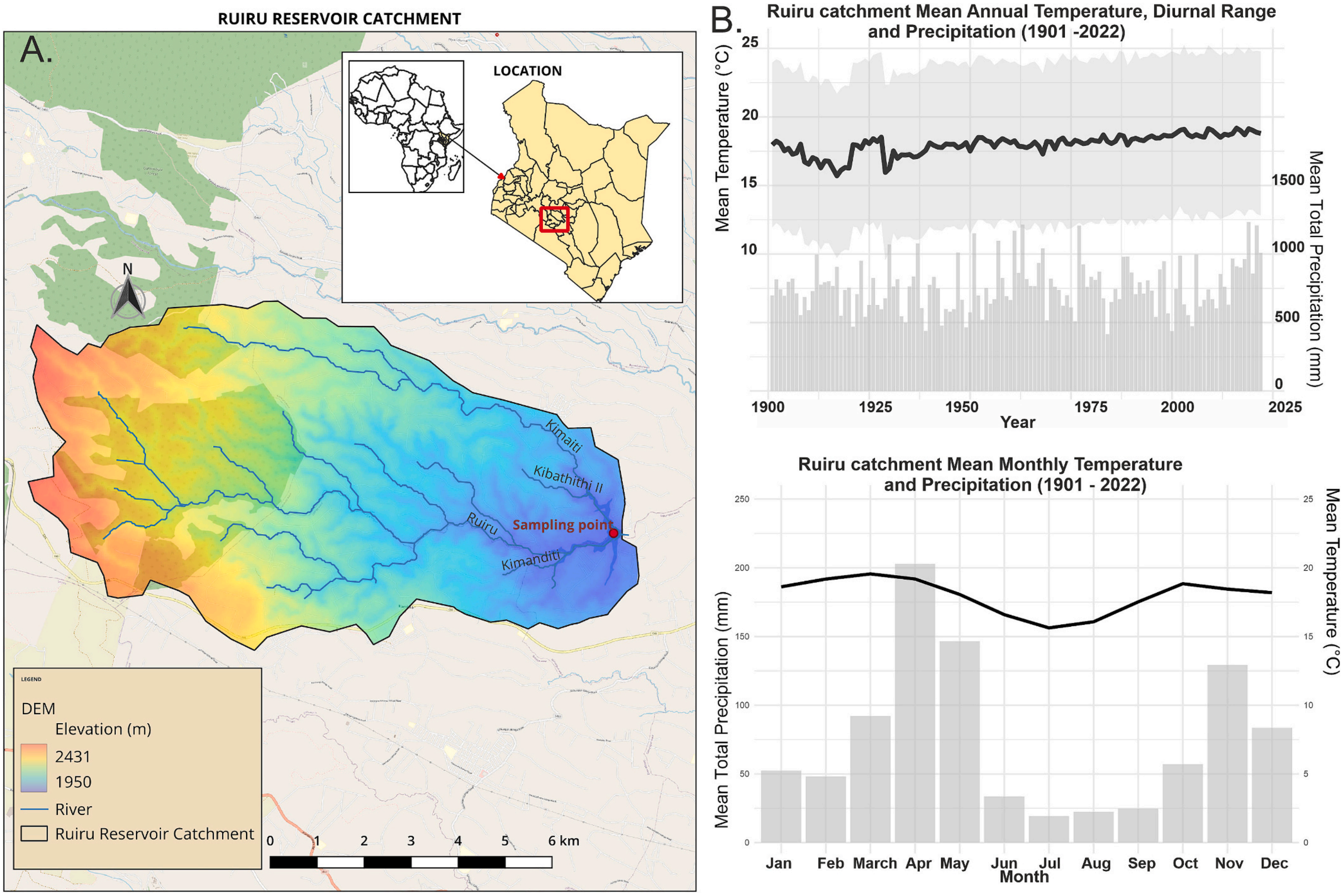

Fig. 1. A. Digital Elevation Map (DEM) of the coring point (1.0472°S 36.7544°E) in Ruiru Reservoir within the catchment in Kenya and Africa. B. Top right is the Ruiru catchment Mean Annual Temperature, mean annual diurnal range and mean total precipitation as a black line, grey band and grey bar graphs respectively for the period 1901 to 2022. The bottom image is a graph showing the mean monthly precipitation (grey bars), and mean monthly temperature1901 to 2022 (black line) from the Climate Research Unit (CRU TS v4.07) (Source: Harris et al., 2020).

color), with a small portion of Andosols found in the upper part of the catchment. The soils are acidic with soil samples taken within the catchment varying between pH 3.78 and 6.81 (Kamamia et al., 2021, unpublished data). The main LULC types within the catchment are annual and perennial cropland, grasslands, forests and built-up areas including settlements (Kamamia et al., 2021; Nyakundi et al., 2015). The land-use potential according to the country's agro-ecological zones is medium to high potential (Waithaka et al., 2020).

2.2. Methodology

2.2.1. Fieldwork

A catamaran (specialized Dual-Jon boats) fitted with dual echo sounder with an in-built Global Positioning System (GPS) was used to survey the reservoir and determine the coring point. The dual echo sounder (Fish finder -Raymarine Dragonfly 87*), was used to locate the point with the deepest water level which was 16 m. A 103-cm long sediment core (RU12–1) was taken on 17th March 2017 from 1.0472°S 36.7544°E, at an elevation of 1970 m asl a central point of the Ruiru Reservoir (Fig. 1). A 2-m transparent PVC liner with a diameter of 90 mm in the UWITEC gravity corer (UWITEC Umwelt- und Wissenschaftstechnik, Mondsee, Austria) with additional weights was used to carefully retrieve the core (core always secured in a vertical position). The corer penetrated the reservoir floor and the retrieved 103 cm total core, can be divided into three units. The fine grained red deposited sediment layer from 0 to 60 cm, coarse grained red soil-sediment mixture from 60 to 80 cm and a red pre-reservoir soil from 80 to 103 cm. Water was drained from the top of the core through a hole bored using a small handheld drill. A block of green floral foam placed on the sediment, inside the core tube stabilized the top and absorbed excess water. The transparent PVC liner allowed for inspection of core quality immediately after coring and ensured that all the eroded material was captured in the core. The core was taped, labeled and transported to the laboratory where it was stored in an upright position while open (albeit with covering to prevent contamination) to complete drying. Slow dewatering ensured the upper sediments consolidate more and become less susceptible to disturbance during shipping.

2.2.2. Laboratory analysis

The core was opened and split lengthwise (one cylindrical core became two half-cylinders) at the German Research Centre for Geosciences (GFZ), laboratory in Potsdam. The lithostratigraphy was described in terms of color, texture and organic matter residue. After the ITRAX XRF scanning, the core was sub-sampled at a 2-cm resolution on one-half of the split core and the second half of the split core at a 1-cm resolution. 139 samples were analyzed; 36 samples at two centimeter resolution for ^{210}Pb dating and 103 samples at one centimeter resolution for the chemical and physical analysis.

2.2.2.1. X-ray fluorescence (XRF) spectroscopy. Non-destructive XRF spectroscopy analysis was performed at the GFZ using the ITRAX™ core scanner following standard ITRAX scanner specifications and procedures outlined in (Thomson et al., 2006). The core scanner was equipped with a Chromium anode and the scan ran with a dwell time of 10 s at an energy level of 55 mA with a 30 kV beam every two microns (2 μm). The results obtained are intensity in counts per second (cps).

2.2.2.2. Chronology sampling. To acquire a continuous chronology of the deposited sediment, 36 samples each spanning 2 cm were sub-sampled from the top (2017) of RU12–1 to 72 cm for gamma spectrometry analysis of unsupported *Lead* (^{210}Pb) and *Caesium* (^{137}Cs) in Ravensburg-Weingarten University of Applied Sciences, Germany. Two centimeters of depth interval was estimated to be the amount of sample needed to acquire sufficient quantity to obtain a volume of 1 cm^3 of dry sediment while maintaining temporal resolution. The samples were oven-dried at 40 °C, coarsely ground, sub-sampled into weighed tubes, and weighed again (mg precision). The activity concentrations were measured with radon-sealed samples on a BEGe 5030 detector with a carbon window (Brenner and Kenney, 2015; Putyrskaya et al., 2015) and analyzed using the Genie-2000 and LabSocs Software (Canberra). The depth of 72 cm was selected as the bottom depth for the ^{210}Pb - ^{137}Cs through visual inspection of the core as a point past the eroded material to ensure all the eroded material was selected for dating. Due to the cost of dating, the dating strategy involves selecting samples to a point assumed to below the accumulated sediment to capture the complete chronology.

The age-depth model was developed from a Constant Rate Supply (CRS) ^{210}Pb model (Appleby, 2005) with a fixed lower point (60 cm = year 1949) at the soil/sediment boundary. Due to the low ^{137}Cs activity concentrations, a model using the sum of two exponential functions as a constant were convolved by a Gaussian curve. The sampled depths, ages and fixed points are shown in supplementary Table S1; the position of the first ^{137}Cs maxima was estimated as 1963 at 55 cm. Levels with peaks in ^{137}Cs are used time-markers due to the atmospheric fallout associated with nuclear weapon testing and nuclear accidents (Putyrskaya et al., 2015; Tylmann et al., 2016). The 1963 maximum fall-out is described as the most reliable ^{137}Cs detectable globally (Foucher et al., 2021).

2.2.2.3. Dry bulk-density, sediment accumulation rate (SAR) and C/N analysis. Dry Bulk density measurements was measured by first sub-sampling the core (1 cm) weighing, drying (oven-dried at 40 °C for 4 days) and then reweighing. Using the corer's cross-sectional area and the thickness of the sampled interval, the sediment volume of the half-core section was calculated using the formula $V = ½\ \pi\ r^2 h$. Bulk density (g cm^{-3}) was therefore calculated as

$$\text{Bulk density}\ (\text{g cm}^{-3}) = \frac{mass\ (g)}{volume\ (cm3)}.$$

Dry bulk density values are presented as the dry weight is used in the sediment accumulation rate calculation. Wet bulk density values are available in the supplementary file.

Sediment accumulation rate (g cm^{-2} yr^{-1}) was calculated by dividing the mass per year by the area using the formula SAR = {(grams/year)/ $½\ \pi\ r^2$}.

Where the radius (r) was 4.5 cm since the diameter of the core was 9 cm and the height (h) was 60 cm. The total core length was 103 cm of which the analyzed deposited sediment was the top 60 cm.

The organic carbon (C_{org}) and total nitrogen were determined by dry combustion using the Vario TOC Cube Elementar equipment (Elementar Analysensysteme GmbH, Langenselbold, Germany).

2.2.2.4. Particle size distribution (PSD) by laser particle diffraction. The second half cylinder of the core was sub-sampled at 1 cm resolution and the samples freeze-dried to remove the inter-granular moisture (Meyer and Fisher, 1997). 1 g of dried sediment was sub-sampled into 250 ml centrifuge bottles (wide-necked with flat base, made from polypropylene polymer (PP polymer) volume = 500 ml, thermally stable up to 110 °C). In a fume hood, 30 ml 30 % Hydrogen peroxide (H_2O_2) (organic matter removal) was carefully added in 3 steps of 10 ml allowing strong reactions if observed to subside. 2-Octanol was added to frothing samples and samples that warmed up intensely were swirled in a cold-water bath to cool them down. Samples were heated to 90 °C in a hot water bath to remove the H_2O_2 that bubbles during breakdown. Samples were observed to ensure they do not dry out during H_2O_2 removal by adding deionized water. After cooling, 25 ml of Sodium Pyrophosphate, c($Na_4P_2O_7$) = 0.1 mol/l was added to the samples and left overnight. Samples were shaken in a shaker to further disperse any aggregates before analysis in the Malvern 3000 particle size laser analyzer (Malvern Panalytical Ltd., Malvern, UK). The Malvern software calculated the distribution abundances within the 0.1–3500 μm range and averaged results of triplicate measurements obtained.

2.2.3. Numerical analysis and visualization

Numerical analyses was performed only on the accumulated sediment which is the top 60 cm. Stratigraphic plots of the geophysical and geochemical properties by time on the y-axis provide a general overview of the analyzed properties through time. This was done using the rioja package in R (Juggins, 2023). A broken stick model (bstick model) was used to determine the number of significant groups to be selected in the cluster analysis (Bennett, 1996). The Constrained Clustering Analysis (CONISS) (Grimm, 1987) is a hierarchical agglomeration of stratigraphically adjacent samples. The CONISS was plotted alongside the stratigraphic plots to illustrate the grouping with the number of zones selected by the broken stick model. The broken stick model identifies the significant number of groups while the CONISS identifies the group borders (depth and time).

To statistically group entire PSDs and correlate them with the lithostratigraphic units, end-member modelling analysis (EMMA) was applied using the R package EMMAgeo (Dietze and Dietze, 2019; Dietze et al., 2022).

A principal component analysis (PCA) on the 11 centered log-ratio-transformed elements (Al, Si, P, S, K, Ca, Ti, V, Mn, Fe and Zr) reduced the dimensionality of the dataset (Jollife and Cadima, 2016) and identified the main elements typifying the sediment. A second PCA on the identified elements, C, N and the grain size profiles led to a selection of the most significant variables.

A Peak analysis across the analyzed properties was used to identify layers where individual or multiple properties peaked. A locally weighted regression (loess) was selected. Loess combines the use of weights from a local polynomial regression with nearest neighbor estimates. The method takes into consideration the trend across the dataset while comparing observations within the neighborhood (Fahrmeir et al., 2021). A factor of 1.2 was selected that identified peaks where the values were higher than 20 % compared to the loess-smoothed value.

2.2.4. Climatological data

Temperature and precipitation data were obtained from CRU TS (Climatic Research Unit gridded Time Series) dataset version 4.07 to produce the rainfall and temperature curves (Funk et al., 2015; Harris et al., 2020). Peak analysis, CONISS, PCA, and EMMAGEO were performed by using various packages (Supplementary Table S3) in R Statistical Software R (version 4.3.2, 2023-10-31 ucrt). CorelDraw Graphics Suite 2022 was used to combine multiple plots into panels.

3. Results

3.1. Chronology

From the 36 dated samples, a chronostratigraphic model dated the eroded sediment back to 1949 at the 58–60 cm sample (marked by the red x at the bottom left of Fig. 2B). The age-depth model indicates the years with the fixed time points used in the model. The fixed time points are 2017 at the top of the core, the ^{137}Cs peak in 1963 (55 cm) and 1949 at the bottom of the eroded material.

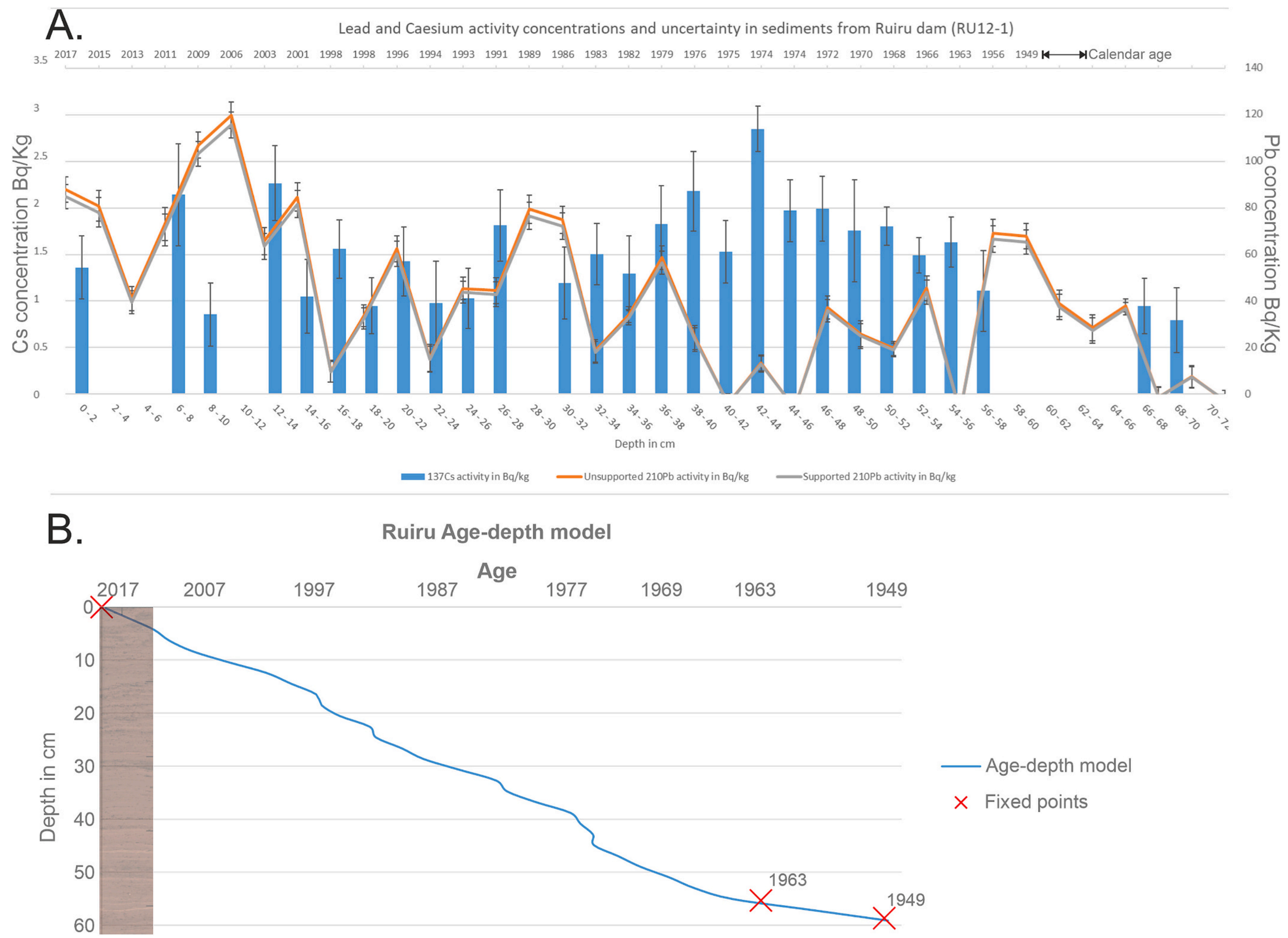

Fig. 2. A) A Constant Rate Supply (CRS) 210Pb model Age depth model developed from 30 dated RU12–1 samples. The x-axis is time and y-axis is depth (cm). The blue line is the modelled age from the modelled 210Pb in Bq cm^{-3}. The red crosses indicate the fixed time points (1949, 1963 ^{137}Cs peak, 2017 from bottom to top). Inserted is an ITRAX scanner image of the sediment core. (2B). A plot of the ^{210}Pb and ^{137}Cs activities as line and columns respectively and uncertainties as error bars.

Fig. 2A. A plot of the ^{210}Pb and ^{137}Cs activities as line and columns respectively and uncertainties as error bars. 2B. A Constant Rate Supply (CRS) ^{210}Pb model Age depth model developed from 30 dated RU12–1 samples. The x-axis is time and y-axis is depth (cm). The blue line is the modelled age from the modelled ^{210}Pb in Bq cm^{-3}. The red crosses indicate the fixed time points (1949, 1963 ^{137}Cs peak, 2017 from bottom to top). Inserted is an ITRAX scanner image of the sediment core.

3.2. Geophysical properties

3.2.1. Sediment core lithology

The retrieved 103 cm core was comprised of three units. The top 60 cm, 60–80 cm and 80 cm to the bottom. From the top (2017) to 60 cm (1949), the eroded sediment was composed of fine-grained red silt with alternating dark and light colored laminations (Fig. 2). The most pronounced dark-colored laminations occur at 0–2 cm, 4–6 cm, 13–19 cm, 23 cm and 38 cm. Light colored laminations occur as thinner laminations at 21 cm, 33 cm, 34 cm, 41 cm, 42 cm, 51 cm, 52 cm, 53 cm and 54 cm. The second unit from 60 cm to 80 cm was a coarse-grained red sediment-soil mixture with two dark colored layers and the bottom section 80 cm to 103 cm was composed mud composed of pre-reservoir local soil.

3.2.2. Dry bulk density (DBD) and sediment accumulation rate (SAR_ - g cm^{-2} yr^{-1})

The dry bulk density (g cm^{-3}) ranged from a minimum of 0.074 in 1994 (23 cm) and 0.33 in 1972 (42 cm) with a mean of 0.15 ± 0.02 g cm^{-3}. A bstick model and CONISS analysis clustered the bulk sediment values into two main groups. From the top to 1974 (43 cm - BD1) and from 1974 to the bottom 1949 (60 cm - BD2). BD1 was further subdivided into three (1 A, 1B, 1C - Fig. 3). The group with the highest BD of 0.24 g cm^{-3} was from 1976 (39 cm) to 1974 (44 cm).

The mean SAR into Ruiru Reservoir was 0.16 ± 0.11 g cm^{-2} yr^{-1}ranging from 0.022 g cm^{-2} yr^{-1} to 0.64 g cm^{-2} yr^{-1}. A bstick model and CONISS cluster analysis grouped the SAR into two main groups (Fig. 3A). The two main zones were Acc_Rate1 from 2017 at the top to 1963 (55 cm) and Acc_Rate2 from 1963 to the 1949 (60 cm). The top group Acc_Rate1 is divided into two groups, from 2017 at the top to 1977 (38 cm) and from 1976 (39 cm) to 1964 (54 cm) a period with the highest sedimentation rate of 0.24 g cm^{-2} yr^{-1}.

The RU12–1 sediment core particle-size distribution was characterized by a polymodal distribution of poorly sorted silt that varied between fine skewed and symmetrical (Supplementary Table S2). A bstick model and CONISS analysis identified four clusters (Fig. 3 A). The top group PSD1 from 2017 at the top to 1986 (31 cm) and PSD2 from 1985 to the bottom at 1949 (60 cm). The end member analysis of the particle size distribution revealed four distinct end-members (Fig. 3B). End-member (EM) 1 with a modal position at 250 μm (medium sand)

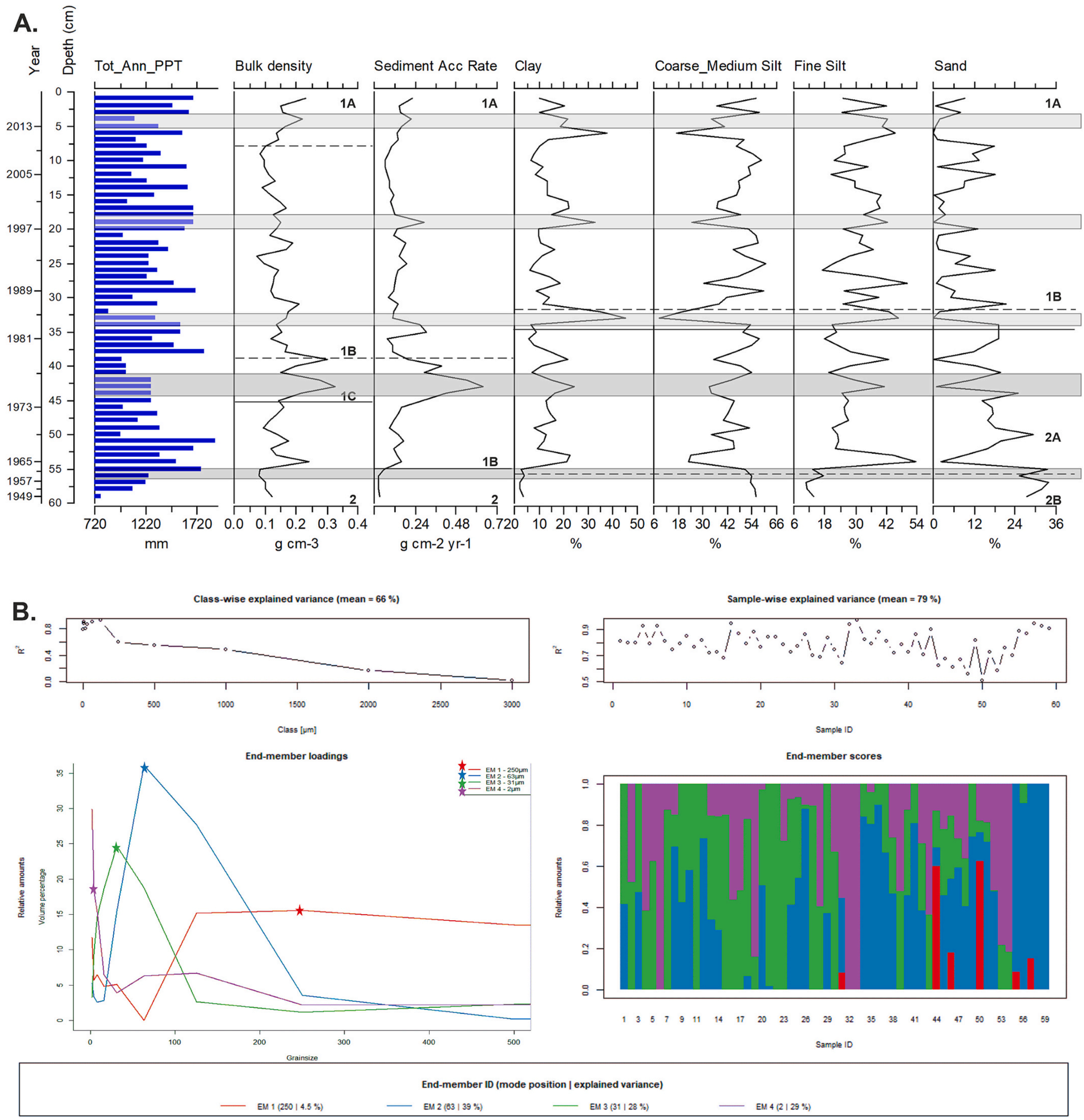

Fig. 3. The total annual precipitation, bulk density, sediment accumulation rate and particle size analysis changes through time (depth). The CONISS clusters are delineated using continuous lines to show the main zones while the dashed lines delineate the sub zones. The periods with peaks in more than five sediment properties are highlighted in grey. B.) The output from the EMMAGEO showing the four identified end members and their modes (μm).

explained 4.5 % of the variance, EM2 with a mode position at 63 μm (coarse silt) explained 39 %, EM3 with a mode position at 31 μm (fine silt) explained 28 % and EM4 with a mode position at 2 μm (clay) explained 29 % of the variance. EM1 closely matches the sand peaks while EM4 closely matches the clay peaks.

3.3. Chemical properties

The mean carbon (C_{org}) content 3.4 ± 0.71 % ranged from 1.2 % to 3.8 % while the mean nitrogen content 0.3 ± 0.06 % ranged from 0.11 % to 0.33 %. The mean C/N ratio was 11 ± 0.38 %. A bstick model and CONNIS analysis clusters the sediment C\N content into two main groups (Fig. 4; Supplementary Table S2). CN1 from 2017 at the top to 1974 (44 cm) and CN2 from 1974 to the bottom of the core 1949.

The bstick model and CONNIS analysis on the elemental measurements clusters the profiles into two main groups and the top group is further divided into three (Fig. 4). ITRAX1 from the top 2017 to 1975 (45 cm) and ITRAX2 to the bottom at 1949 (60 cm). A principal component analysis (PCA) identified Mn, Fe, Ti, K as well as Ca as the most significant elements. Axis 1 explained 94.1 % of the variance and

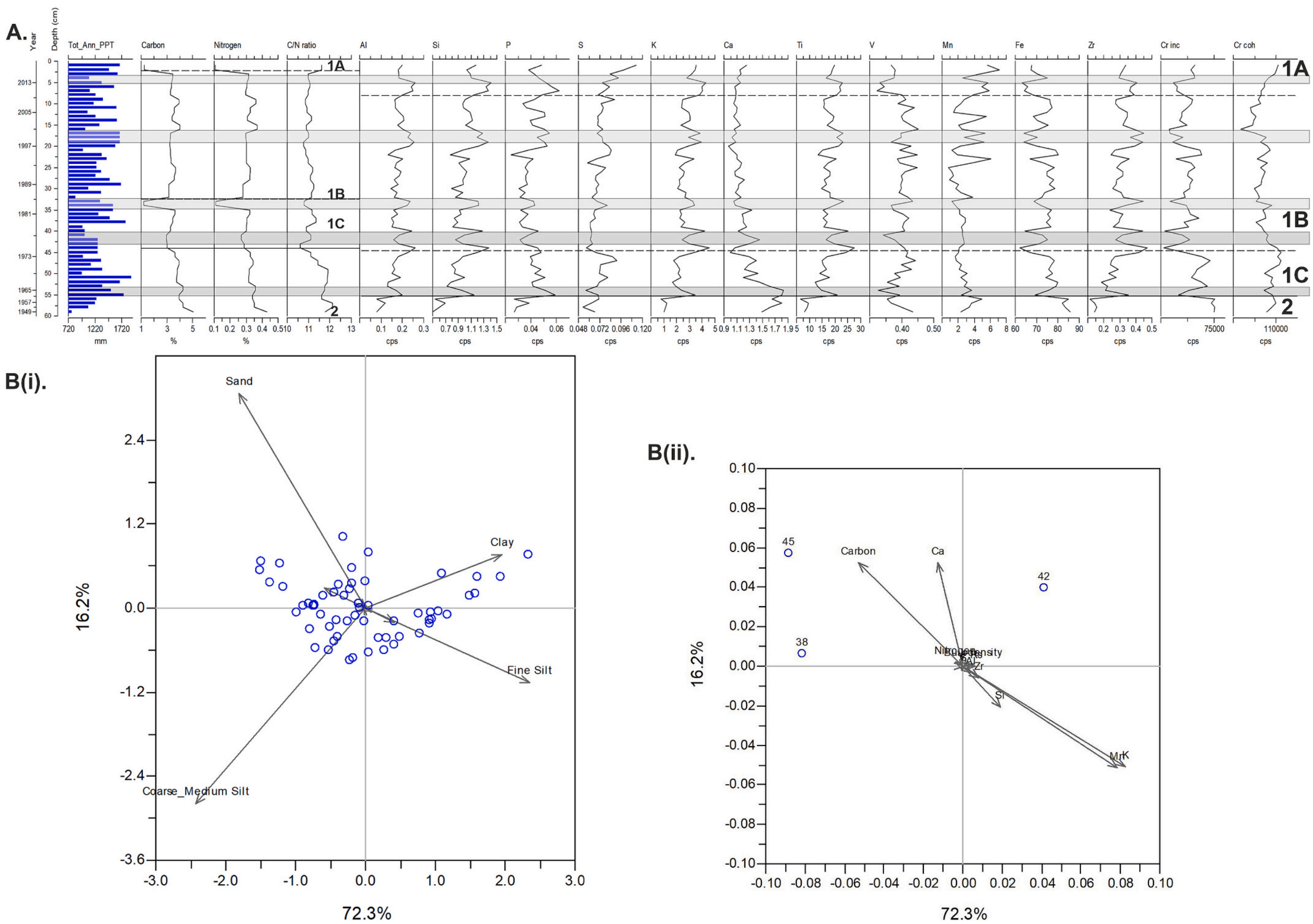

Fig. 4. A) The geochemical properties – C, N, Al, Si, P, K, Ca, Ti, V, Mn, Fe and Zr measured and their associated CONISS cluster diagram. The continuous line shows the main zones while the dashed lines delineate the sub zones. The grey bands highlight the periods of increased sedimentation into the reservoir when more than five of the analyzed peaks record peak values (20 % higher than the LOESS average). B (i). The PCA output showing the distribution of the geochemical and geophysical properties, the x-axis ranges between −2.5 and 2.5 representing coarse_medium silt and clay respectively. B (ii). is an inset of B(i) to provide a close up view of the properties centered in the PCA diagram.

axis 2 explained 5.7 %. A PCA on the identified significant elements combined with the measured geophysical properties explained 88.5 % of the. Axis 1 explained 72.3 % while axis 2 explained 16.2 % of the variance. For the combined PCA (Fig. 4B), the first axis spans from positive species scores for clay, fine silt and Ti and negative for sand, coarse_medium silt and Fe. The second axis spans from positive score of sand, clay Fe to negative score of silt and Ti.

3.4. Peak analysis

A locally weighted polynomial regression was used to smooth the data and provide trend lines for each of the properties analyzed (Supplementary Fig. S4). Of the 21 variables analyzed, no peaks were detected in Fe, V or CN ratio (Fig. 5). Peaks were observed in more than five proxies in 2013/14, 1997/98, 1982/83, 1974/75, 1963 and 1949 (Supplementary Table S2).

4. Discussion

The analysis of the pathways and fate of eroded sediment from a catchment to a water reservoir can be technically challenging. To gain a comprehensive understanding of the processes involved in erosion, transport, and sedimentation, it is essential to examine records from different regions representing various aspects topography, land-use types and sedimentology (Arnaud et al., 2016). Such a multi-faceted approach enables the development of robust and detailed historical reconstructions allowing for global level analysis that represent all possible scenarios.

Sediment source studies have therefore been applied in catchment studies to assess the sediment budget and the sediment sources (sediment source fingerprinting (Collins et al., 2020)) through targeted soil erosion measures. Through the testing and development of sample and data analytical techniques, sediment has been used to identify soil erosion hotspots and sediment chemical composition (Koiter et al., 2018; Liu et al., 2016; Manjoro et al., 2017; Pulley and Collins, 2021; Vale et al., 2022). However very few studies (Amasi et al., 2021; Florsheim et al., 2011; Foster and Walling, 1994; Junge et al., 2018; Navas et al., 2009; Owens et al., 1999) utilize the sediment as an environmental archive of high resolution 20th century change analyzing the environmental impacts of climate change, agriculture, forestry, and land uses on water reservoirs.

At the Ruiru Reservoir, the sediment in the dam is derived from the catchment within an area of 51 km^2 from the time the dam construction was completed in 1949. The continuous sampling of the RU12–1 sediment core provides the highest resolution possible to give us a temporal insight, comparable with the available measured proxy data. ^{210}Pb dating of short cores that are relatively young (∼150) years has been used extensively in East Africa (Kiage and Liu, 2009; McKee et al., 2005; Öberg et al., 2013; Verschuren, 1999) and tend to be validated by independent variables such as ^{137}Cs, varves (Tylmann et al., 2016), tephra

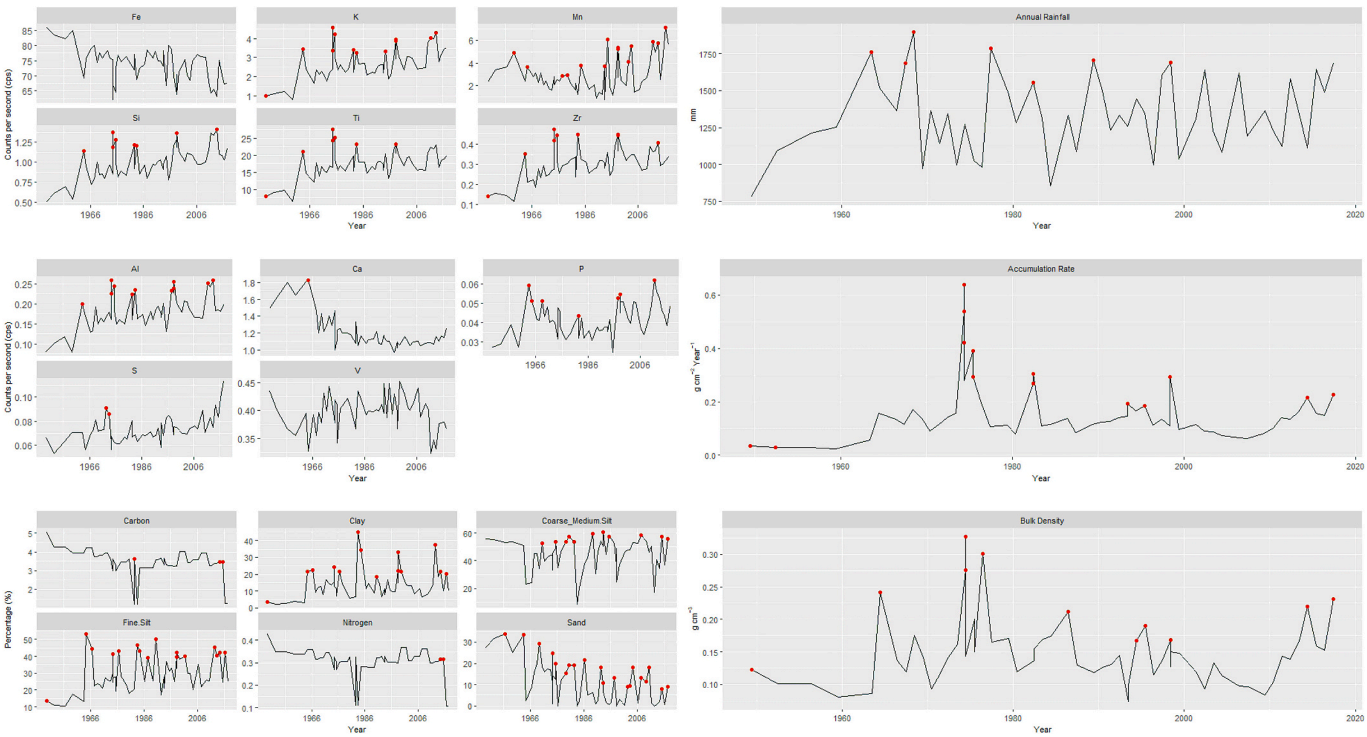

Fig. 5. Time series analysis of the geophysical and geochemical properties with 20 % LOESS peaks marked by the red circles.

layers (Johnson et al., 2011; Martin-Jones et al., 2020; Pyle, 1999) or known start of deposition date as is the case in a manmade reservoir (Kunz et al., 2011). The independent known time markers applied to the RU12–1 core were the 1963 ^{137}Cs peak, the start year of sedimentation (1949) and the top coring date (2017). The 1963 ^{137}Cs peak has been observed and used as a time marker in several east African records (Bittner et al., 2020; De Cort et al., 2013; Foucher et al., 2021; Stoof-Leichsenring et al., 2011).

At Ruiru Reservoir, combining the analysis of geochemical and geophysical properties is crucial to develop an understanding of the sediment deposited in the reservoir. Combining multiple environmental proxies allows a comprehensive understanding (Schillereff et al., 2014). The analysis and presentation of the particle size, elemental composition, and accumulation rates explain the sediment properties and the processes driving sedimentation accumulation in Ruiru Reservoir. The extent to which these different properties respond in unison reveals features such as periods of peak sediment accumulation and can identify sediment source area or processes driving accumulation rates into the reservoir. Delineating zones of the analyzed properties is useful for independently identifying if the different proxies are responding at the same time. Overlapping zones across the different properties signifies that an observable change in condition is supported by multiple properties.

4.1. Sediment deposition patterns

The RU12-1 core is composed of accumulated material eroded into the reservoir; P, K, Mn and Zr are the main elements in the fertilizers used in the region. In the RU12-1 core, the laminations observed coincide with the peak levels of accumulation rate. A positive correlation between discharge energy and particle size is often observed. Fine grained silt and clay would reflect sedimentation during slightly elevated flows while coarse-grained layers would reflect the highest energy input (Schillereff et al., 2014). At Ruiru, dark-colored thick laminations often coincide with high levels of Mn, clay and BD. Thin light-colored laminations coincide with sand, rainfall and SAR peaks. Laminations in East African lake sediment records have been used to represent seasonality in Lakes Bosumtwi and Baringo (Kiage and Liu, 2009; Shanahan et al., 2012), and lake levels in Lakes Kivu and Tanganyika (Haberyan and Hecky, 1987). Use of sediment traps at Lake Challa produced alternating light and dark laminations reflecting seasonality and where lamination thickness was related to the strength and duration of the windy season (Wolff, 2011). At Ruiru, the dark and light alternating laminations of different thickness could represent variation in sedimentation from different sources or the sedimentation in layers during onset of the rainy season. Ruiru Reservoir has never dried exposing the sediment since its construction and sediment color changes due to exposure are not expected. The resolution of one year in the analysis does not allow discernment of the seasonal rainfall signal. Use of sediment traps could be applied to resolve the seasonality and event based aspect in reservoir studies (Apolinarska et al., 2020; Kristen, 2010).

Bulk density values and SAR are indicators of the amount of sediment accumulating in the reservoir. In Ruiru Reservoir they can be grouped into two main phases: The first phase from the start of the use of the dam in 1949 to 1977 and from 1977 to present. From 1949 the DBD and SAR values were low for the first 15 years but they significantly increased in the period 1964 to 1976 with a peak occurring at 1974–1975. From 1977 to 2017 they decrease and maintain a consistently low value until 2011 when an increasing trend re-emerges. DBD and SAR record periods of increased accumulation due to their contemporaneous peaking together with geochemical and geophysical properties that are indicators of terrigenous input. The RU12–1 DBD peaks match both the clay and sand peaks because the DBD peaks track periods with increased sediment accumulation irrespective of the process driving the erosion and accumulation into the reservoir.

Bulk density varies widely depending on sediment type, for example forest soils from Nandi and Kakamega in western Kenya have a BD value 0.65 g cm^{-3} and 0.76 g cm^{-3} respectively (Solomon et al., 2007) while lacustrine and littoral sediment samples from Lake Kariba in southern Africa range between 0.1 and 1.8 g cm^{-3} (Kunz et al., 2011). The BD of soil samples from the Ruiru catchment has a mean of 0.65 g cm^{-3}

ranging between 0.4 g cm^{-3} and 1 g cm^{-3} (Kamamia et al., 2021) while the mean DBD of the Ruiru Reservoir sediment of 0.15 g cm^{-3} is lower.

The RU12–1 mean sediment accumulation rate 0.16 $\pm$ 0.11 g cm^{-2} yr^{-1} is higher compared to Lake Naivasha which ranges between 0.01 and 0.08 g cm^{-2} yr^{-1} (Stoof-Leichsenring et al., 2011). SAR at Lake Kariba (Zambia/Zimbabwe) ranges between 0.07 and 0.21 g cm^{-2} yr^{-1} (Kunz et al., 2011) which is lower than the RU12–1 mean SAR value. A multicore study from Lake Tanganyika attributed differences in sedimentation rate to disturbance and specifically deforestation in the watershed, where the sediment accumulation rates ranged between 0.005 and 2 g cm^{-2} yr^{-1} (McKee et al., 2005). The sedimentation rate variability along the RU12–1 core can be further distinguished once the sediment source area is resolved.

Field and modelling studies investigating particle size, river flow parameters and relationship between rainfall and grainsize fill the gap in regions lacking long-term monitoring data. In Malaysia, bigger particle sizes are observed during the rainy season compared to the dry season (Selangor Dam, Malaysia (Hairan et al., 2023)), while in the Lanang River basin in Indonesia peak discharge values corresponded to peak rainfall values (Kencanawati et al., 2023). The particle size analysis of RU12–1 reveals that the sediment is predominantly poorly sorted silt. Sediment dynamics are discernable from the changes in the fine silt, clay and sand content. An end member analysis of the particle size distribution allows unmixing of the particle size distributions into end members representing different mechanisms (Schillereff et al., 2014). In the Ruiru reservoir sediment core, the end-member modelling analysis (EMMA) identifies four end members. End member 1 represents the highest-energy erosion events characterized by sand content (mode position of 250-μm). End member 2 having a mode position indicative of coarse silt (63 μm) represents the regular erosion of the medium and coarse silt when there is heavy rainfall. End members 1 and 2 probably represent erosion into the reservoir caused by high energy rapid energy rainfall events with EM1 representing extreme events such as El Nino and EM2 representing higher than average rainfall. Finally end members 3 and 4 having a mode position indicative of fine silt (31 μm) and clay (2 μm) represent erosion into the dam when there is higher than normal erosion of finer sediment in the catchment. EM3 could represent the background erosion into the reservoir. While EM4 could represent erosion in the landscape when the rains fall after a prolonged dry period leading to an increase in the fine grained sediment particles which have become dry and loose after prolonged rainfall absence. EM4 could also represent erosion from intensive or extensive land-cover conversion where initial land breakage is often accompanied by high amount of dust.

Geochemical elements signaling terrigenous input have been used to identify periods of high erosion within the catchment that result in increased sedimentation in the reservoir. Flood layers can be identified through the combination of grain size characteristics and enrichment in lithogenic elements (Croudace and Rothwell, 2015; Kämpf et al., 2011; Schillereff et al., 2014; Wilhelm et al., 2022). Periods of increased sedimentation in Ruiru Reservoir display peaks in sediment accumulation rate, fine silt, clay, and chemical elements. In the Ruiru sediment core, shifts in Al, Si, K, Ti, Mn and Zr closely correspond to clay. This could imply an input of clayey silt with high Ti and Zr sediment origin.

The chemical signal of the accumulation layers could distinguish the allochthonous sediment input as predominantly rich in organic or minerogenic content (Kunz et al., 2011). Distinguishing between allochthonous (terrestrial) versus autochthonous (aquatic) organic matter (OM) is a crucial issue in identifying the nature of the organic matter. C/N ratios $\leq$10 are used as indicators for primarily autochthonous-derived OM (non-vascular aquatic plants) while terrestrial higher plants are characterized by >20C/N ratios (Meyers, 1994; Meyers and Ishiwatari, 1993). The RU12–1 core has a fairly stable C/N ratio between 10 and 12 suggesting a fairly stable mix of algal matter and vascular plant matter (Meyers, 1994).

4.2. Sediment deposition drivers

Of the twenty geophysical and geochemical properties analyzed, peaks were observed in 17 of them. Depths where more than one third of the properties peaked were identified as peak periods. Significant sediment accumulation periods in the reservoir are observed in 1949 1963/64, 1974/5, 1982/3, 1998, and 2013/4. The 1949 accumulation rate peak is expected due to the initialization of reservoir use. Preparing the landscape for reservoir construction might have led to an area of bare land surrounding the newly constructed reservoir which contributed to the initial load of significant sediment into the reservoir.

The 1998, 1982 and 1963 peaks co-occur with significant rainfall. Some regional extreme events causing floods such as in 1961/62/63, 1982 and the 1997/98 El Nino are observed in the local precipitation records (analyzed in this study as total annual precipitation peaks) (Opere, 2013; UNDP, 2007). The 2013/14 peak can be attributed to higher than average rainfall that year after lower than average rainfall for the five preceding years. The periods associated with peaks in annual rainfall show peaks values in sand, sedimentation rate and almost all the chemical elements analyzed. This implies an indiscriminate erosion of soil into the reservoir irrespective of source.

The first priority for the post-independence government of Kenya was the resettlement of former white owned farms. In the 1970s, the government instituted the National Soil and Water Conservation Programme in response to the significant soil conservation issue (Tiffen et al., 1996). This led to increased land sub-division and conversion of land cover from one form to another. In the Ruiru catchment, the significant land use change was from previously natural land cover of forest, shrubland and grassland to farming. The 1974/75 peak is attributed to this significant land-use change in the catchment. The 1974/75 peak is a culmination of intensive land-use change from forest into tea plantations starting around 1964. The land-use change was significant enough to warrant the commission of the Kambaa Tea Factory in the area accompanied by construction of feeder roads to ease transportation of tea from the farms to the newly commissioned tea factory.

The hypothesis that sedimentation into the reservoir has intensified over time highlights that the issue is rather complex. The SAR shows that the two periods with increasing accumulation were 1963–1976 and 2011 to present. The highest accumulation rate into the reservoir occurred from 1963 to 1976 before decreasing for 35 years. Tea growing and dairy farming are prominent land uses in the Ruiru landscape. In recent years there is no evidence of conversion of land from forest to tea plantations. Dairy farmers in the area cultivate Napier grass as a conservation measure and as a source of fodder for their livestock. Both established tea plantations and Napier grass act as sediment traps and reduce the amount and rate of soil erosion, thus the stable lower SAR observed between 1977 and 2011. The SAR has been on an upward trend since 2011 but not to the previously observed levels between 1963 and 1976. The recent increase in sedimentation rate (2011 to present) could reflect changes in the wider landscape where large scale road construction has been taking place since 2009. This assumption is currently under study.

Using the sediment core RU12–1, we can separate background soil erosion from erosion related to high-energy events. Rapid high-energy events are identified in the record by the clear correlation between the patterns and concurrent peaks in the terrigenous input indicators. An understanding of the threshold needed for extreme high energy rainfall events to cause erosion which is observed in the sediment record needs to be developed. A number of local rainfall peaks are not accompanied by an increase in sedimentation. This is a crucial observation as it is important to not assume that all past heavy precipitation events will have an observable signal on the record. In RU12–1 the periods with significant sedimentation peaks are preceded by the driest year while comparing with the previous three years.

4.3. Implications for water resource management

Sediment accumulation in reservoirs is a valuable indicator of catchment processes, providing insights into how land use, weather events, and management practices impact sedimentation rates and the physical, chemical, and biological properties of the sediment. Reservoir managers can use sediment accumulation data to inform management decisions and optimize resource allocation.

In the case of Ruiru Reservoir, the management has changed several times during its 75 year use. It was commissioned and constructed by the British colonial government, transferred to the national government after independence (1963) and to county government management after the constitutional change in 2010. Transfer of largescale infrastructure ownership can sometimes lead to loss of management information due to changes in the administrative processes. A long-term sediment core analysis provides an independent continuous source of data about deposition into the reservoir.

Understanding sedimentation rates in the past and over time helps identify trends and correlate them with specific catchment events or management interventions. At reservoirs with historical management data, the sedimentation data can be used to assess the effectiveness of past reservoir management strategies. If interventions were aimed at reducing sedimentation, the sedimentation data can inform whether these efforts led to measurable changes.

Long-term sedimentation data can be used to link sedimentation to catchment processes by correlating with land cover changes (Collins et al., 2020). Sedimentation rates can be compared with historical land cover data to determine if changes in land use (e.g., deforestation, agriculture) influenced sediment accumulation in the reservoir. The data can also be compared with weather data to assess the relationship between significant weather events (e.g., storms and floods) and spikes in sedimentation rates (flood layers (Kämpf et al., 2011; Wilhelm et al., 2018)). This helps in understanding how extreme weather contributes to erosion and sediment transport. This can be coupled with sediment trap data which can be used to monitor current sedimentation and weather data providing data that can be tested on past long-term observations to test and develop models relating weather patterns and sediment accumulation. Impact of land-use policies on sediment deposition can be evaluated. For example, if new agricultural practices or soil erosion mandates were introduced, they can be checked whether they correlate with changes in sedimentation.

Characterizing accumulated sediment by analyzing the physical, chemical, and biological properties of the accumulated sediment to understand the type of materials being deposited is important for reservoir management. The particle size distribution, organic content, and contaminant levels (Lintern et al., 2016; Sedláček et al., 2013) would have different impacts depending on the main use of the reservoir. For example drinking water reservoirs have different physical and chemical quality characteristics compared to hydroelectric reservoirs.

Once the reservoir managers have a sufficient understanding of the accumulated sediment. Similar analyses can be performed on soil samples from the catchment and river channels to trace the origin of the sediment. This source to sink approach helps in identifying specific erosion hotspots which is important for advanced analysis and mitigation resource allocation.

After establishing baseline sediment properties, advanced targeted biological and chemical analyses can be conducted to identify specific pollutants or biological markers that could indicate particular erosion sources or land-use impacts dependent on the reservoir and catchment under management.

Once key sources of erosion are identified, resources for landscape and reservoir management can be prioritized based on these findings. For instance, focus erosion control efforts on areas contributing the most sediment. Continuous monitoring of sedimentation rates and sediment properties to track the effectiveness of management practices and adjust strategies as needed can be improved by using the insights gained from the long-term sediment data to adapt land-use policies, catchment management strategies, and reservoir maintenance practices, ensuring they remain effective in reducing sedimentation.

By systematically analyzing sediment accumulation data, reservoir managers can gain a deep understanding of catchment processes and make informed decisions to improve reservoir management. This approach not only helps in maintaining reservoir capacity but also supports sustainable land use and environmental conservation in the catchment area.

The study has demonstrated that the sediment accumulation into Ruiru reservoir has occurred at a stable rate since the completion of the dam construction. However, intense rainfall periods and land-use change episodes have led to observable periods of significant sediment accumulation. The long-term approach highlights the importance of applying an environmental interpretation aspect and using historical land-use and climate data to discern the ecological processes and their potential impact on infrastructure. For example a short term study covering the last thirty years from the Ruiru watershed could lead to the assumption that the reservoir has been experiencing a continuous trend of increasing sedimentation deposition rate while the long-term view shows that since construction the sediment deposition rate varies between periods of stable sediment input into the reservoir and periods of significant input with differing drivers.

The insights gleaned from Ruiru reservoir have far-reaching implications that extend beyond local or regional boundaries. Globally, reservoirs face the dual pressures of climate change and increased anthropogenic activities, which exacerbate sedimentation issues and threaten water security. By utilizing the sediment accumulated to understand the sedimentation history of Ruiru reservoir we can draw parallels to other reservoirs worldwide, highlighting common patterns and unique challenges. Reservoirs constructed in the 20th century have now accumulated sediment for ~100 years, the accumulated sediment should be utilized to inform us of catchment dynamics as we have shown. This knowledge is crucial for developing effective sediment management strategies, which are essential for maintaining reservoir capacity, water quality, and ecological health from more than a sedimentary budget point of view. Furthermore, our study underscores the importance of integrating long-term land-use, geological and environmental data to inform policy and engineering solutions. International collaboration and knowledge exchange are vital in addressing these global challenges, ensuring that reservoirs continue to serve their critical functions in a sustainable manner. Our findings contribute to this global discourse, offering a template for similar studies and interventions in diverse geographical contexts to develop a network of high resolution environmental, land-use histories and catchment dynamics.

4.4. Limitations and potential biases in sediment core analysis

Sedimentation is a universal challenge that affects the longevity and efficiency of reservoirs globally, impacting water supply, flood control, and ecosystem services. However by elucidating the historical sedimentation patterns and identifying the driving environmental processes in the catchment there is an opportunity to access environmental change data that can be used for ecosystems change analysis, land-use change analysis and sustainable reservoir management.

The integration of established, advanced and readily available analytical techniques, such as radiometric dating and geochemical and geophysical profiling, demonstrates a comprehensive and inclusive approach to understanding sediment dynamics. These methods can be employed by researchers and practitioners internationally to enhance sediment management practices. The multi-proxy approach has been useful in dissociating sediment accumulation caused by intense precipitation and land-use change. Combining the geochemical and geophysical characteristics with precipitation data has shown that periods with intense rainfall can be identified and that rainfall is not the only process causing significant sediment accumulation into the reservoir (rainfall explains three of the five identified peaks). Further chemical and biological analysis will separate the elements into the organic and inorganic matrix and provide the links to the different land-use practices in the catchment.

To effectively understand past changes in a catchment area through sediment core analysis, high-resolution dating is crucial. Accurate dating of sediment allows for a stronger correlation between catchment dynamics and the sediment deposited, making it possible to link specific sediment characteristics to land use or climatic events with greater confidence. However, the cost of sediment dating can be a significant barrier. Knowledge about the study site can optimize decision making while developing a dating strategy since bioturbation, plant growth, erosion events, temporary drying of the wetland can cause errors in the age calculation.

Interpretations of sediment data should be corroborated with independent sources, such as historical climate or land use records. Since soil erosion can result from both natural and human activities, reliable external data is essential for validating interpretations.

The Ruiru study includes a SWAT analysis to delineate the catchment boundary, which is crucial for accurately describing dynamics such as slope and tributary behavior within the defined catchment. For Ruiru dam, the associated river is a source of sediment. Any similar research of a reservoir with input from a river should therefore start with a catchment delineation step to ensure that the analysis is confined to the relevant catchment area, providing consistency and comparability in understanding the catchment dynamics.

The study identifies peak sedimentation periods by correlating historical precipitation data with historical land-use information (conversion of forest to agriculture), though precise details such as the area of land-use conversion (tea, annual crops, perennial cops) are lacking. Due to limitations in data resolution where one sediment sample represents a whole year, high precipitation events whether seasonal or single-event based events cannot be captured. As a result, the current analysis links sediment characteristics with the available precipitation and land-use change data at an annual scale. When extrapolating these findings to other regions, it is essential to consider similar data limitations. Regions with more detailed land-cover, land-use data, and high sediment sampling resolution could provide more precise results such identifying rainfall seasonality in the sediment record. In areas with data availability constraints, the approach offers a practical method for understanding sedimentation dynamics despite incomplete catchment data.

5. Conclusion

The study presents a 70-year sedimentology history of a water reservoir providing potable water to the Kenyan capital city and can support evidence-based decision-making for sustainable land and water management practices by providing targeted recommendations. By presenting the sedimentary sequence, we evaluate the catchment processes driving sedimentation into the reservoir. The results show the utility of using multiple parameters to understand the impacts of land-use and weather events over time on the landscape and on infrastructure. Sediment accumulation into Ruiru reservoir has been substantiated as occurring in a stable pattern except during periods of high rainfall precipitation or extensive land-use change in the catchment. Periods of significant sedimentation are clearly observable in the physical and chemical characterization of the deposited sediment as well as combination with the annual precipitation records and the land-use history of the catchment. The findings therefore accept the hypotheses: sediment accumulation has intensified over time; periods of high sedimentation are observable and high energy events lead to significant erosion and sedimentation into the reservoir. However the hypothesis sediment accumulation has intensified over time always needs to be critically assessed as the record shows a previous period of high sedimentation which then decreased.

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CRediT authorship contribution statement

Esther Githumbi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Ann Kamamia:** Writing – review & editing, Writing – original draft, Visualization. **Lucas Kämpf:** Writing – review & editing, Writing – original draft, Methodology. **Hosea Mwangi:** Writing – review & editing, Writing – original draft. **Joseph Karanja:** Writing – review & editing, Methodology. **Michael Zech:** Writing – review & editing, Writing – original draft. **Stefan Julich:** Writing – review & editing, Writing – original draft, Funding acquisition. **Karl-Heinz Feger:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

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.

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Data availability

The supplementary data contains all the data used in the study

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