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Use of ^{210}Pb and ^{137}Cs Radionuclides as Simple Method of Estimating Sedimentation Rates on Reservoir

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ABSTRACT

Reservoirs are important for flood control, production of hydroelectric power, fishing, water harvesting and storage. Climate is changing, population and anthropogenic activities are increasing which increase sedimentation rate to most of reservoirs reducing their capacity. With climate change in mind water are becoming scarce resources which need proper storage when available and suitable flood control in areas with unpredicted rainfall. Furthermore, population growth and increases energy demand suggesting that there is a need of sustainable management of dams so as to control flood, produce more hydroelectric power and store water for use in dry season. Sedimentation is one of the factors influencing storage capacity of the reservoir. Understanding sedimentation rate, source of sediment and carryout proper management measures is one among of the important methods to preserve dams. ^{137}Cs and ^{210}Pb are important radionuclides for investigating sedimentation rate in reservoir. The method has been used for more than two decades in developed countries with less use in developing countries. In this study a sediment core was sampled at the centre of Nyumba ya Mungu reservoir in Tanzania then the samples were transported to China for processing and analysis. High-purity Germanium detector was used to analyze ^{210}Pb and ^{137}Cs. The results showed that rate of sedimentation in the reservoir ranged from 0.21 to 0.65 cm/year with more sediment coming from Kikuletwa than Ruvu tributary. Proper utilization of this method can bring sustainable management of water, save communities from flood disaster and high production of hydroelectric power.

INTRODUCTION

Global increase in GHGs emission has caused additional warming on the earth's surface [1]. This increase is expected to have serious disastrous impacts in various sectors such as increase need of energy for cooling while change in precipitation can affect hydroelectric power production. In transportation sector, increase in rainfall can cause disruptions of railways and roads. In addition to that, the Intergovernmental Panel on Climate Change (IPCC) confirmed with substantial evidence that the mean and extremes of climate variables have been changing in recent decades, and that rising atmospheric greenhouse gases concentrations could cause the trends of climate variables to intensify with more impacts in the coming decades [2]. Therefore, climate change impacts are expected to increase in future compared to the current observed impacts if no serious measures taken into consideration. Even though climate change will affect many sectors but its effect on water resources seems to be more severe than other sectors especially to developing countries located in arid and semi-arid depending on rainfall for social and economic development [2].

Adaptation to climate change is the only important option to cope with the change in climate. Construction of water reservoir is among of a crucial way of

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controlling the natural character of water flows, as an alternative of depending on rainfall. Reservoirs are designed to have a high level of multi-functionality such as collecting water from upstream and supply them in organized way downstream, production of hydroelectric power, irrigation, navigation and flood control to the population downstream.

With climate change in mind reservoirs are helping communities in different ways such as water shortage problem. In addition to that Ramalho et al investigated how location of reservoir can help in fighting against forest fire [3]. The authors concluded that global warming will increase incident of forest fire therefore reservoirs can be placed in areas with high- and very high-risk of fires to reduce the risk.

Besides climate, there are other drivers of global change, including population increase, economic development and urbanization [4]. These change will increase demand for water resources and energy of which water reservoir is one among of the methods to minimize water shortage and increase production of hydroelectric power.

Anthropogenic activities are the major contributor of soil erosion leading to sedimentation in the reservoir. In addition to that rate of soil erosion and the quantity of soil taken to the reservoir (sedimentation) depend on various factors such as soil type, the topographic, vegetation type, geology, climate, and land use within the catchment [5].

It is clear that reservoirs are important to increase accessibility of water to the communities as well as increasing production of hydroelectric power and irrigation activities. Nevertheless, sedimentation is crucial factor influencing reservoir storage capacity [6], production of hydroelectric power [7], increasing flooding risk, decreasing availability of water for irrigation, navigation, wildlife and other domestic use [8,9]. It was estimated that about 45 km^3 per year of sediments are trapped by the dams worldwide decreasing dams storage capacity of around 0.8% and loss of revenue around 13 billion USD per year [10]. Furthermore, it was reported that if mitigation measures are not taken into account majority of reservoirs will completely lose their storage capacity within the next century [11].

Nyumba ya Mungu "House of God" reservoir is among of the reservoir decreasing storage capacity and production of hydroelectric power [12]. Nyumba ya Mungu reservoir is large man made reservoir in Pangani River basin-Tanzania that was constructed for many purpose such as irrigation, water supply, flood control and production of hydroelectric power [12]. Studies showed that the reservoir has high trap efficiency ranging from 20% to 90% [13]. Additionally, the estimate showed that Nyumba Ya Mungu reservoir has high residence time of about 18 months [14]. High trap efficiency and high residence time causes the reservoir to be a sink of nutrients, organic carbon and metals [13, 14].

Mitigation measures to reduce soil erosion and sedimentation in the reservoir will only be possible after a clear understanding source of sediments, causes of sediments erosion and sedimentation rate. In Nyumba ya Mungu reservoir, Maureen et al. [15] used Magnetic properties of sediments to investigate sources of sediment in the reservoir whereas Msovu et al. [16] found that increasing rate of soil erosion has been contributed by land use land cover change accelerated by anthropogenic activities. Furthermore, no study was conducted to estimate sedimentation rate in Nyumba ya Mungu, therefore this study was conducted to estimate sedimentation rate. Understanding sources of sediments, causes of soil erosion and sedimentation rate can help for management measures to reduce sedimentation rate in Nyumba ya Mungu reservoir.

There are various methods of estimating sedimentation rate such as remote sensing method of which its main limitation is that it is not suitable for reservoirs located in a narrow steep-sided valleys, where the surface area of the water body exhibits little change over a range of water levels [17]. Inflow and outflow is another method of estimating sedimentation rate but require extensive calculations of sediment yield, amount of eroded soil, sediment inflow and the quantity of water flows into the reservoir [18]. The use of various radionuclides such as ^{90}Sr, ^{60}Co, ^{137}Cs, and ^{210}Pb among others have become a common and simple method of estimating sedimentation rate in reservoir. Wide application of ^{210}Pb started 1960s after successful testing hypothesis of Goldberg in Greenland ice-sheet [19], whereas widely use of ^{137}Cs occurred after nuclear weapon testing [20]. Therefore, this study used ^{210}Pb and ^{137}Cs to estimate extent of sedimentation rate in Nyumba ya Mungu reservoir. Feedback from this study can suggest on what need to be done for short and long term plan in managing the reservoir.

MATERIALS AND METHODS

Study area

Nyumba ya Mungu reservoir is a large man made reservoir with an area of 180 km^2 and a mean depth of 6 m [21]. It is located in an arid area of Pangani River basin on the slope of Mt. Kilimanjaro. It was constructed in 1965 for irrigation, water supply, flood control and production of hydroelectric power [12]. A hydro plant of 8.0 megawatts capacity is constructed within the reservoir which consists of two units each with 4.0 MW capacity [22]. With sedimentation and low rate of rainfall the reservoir is producing less electricity than planned. Kikuletwa and Ruvu Rivers are two main rivers pour water into the reservoir (Figure 1).

The reservoir experiences tropical type of climate in which north-south movement of inter-tropical convergence zone (ITCZ) enable the reservoir to have bimodal type of rainfall [23]. March to May is long rainy seasons which occurs when ITCZ moves from equator to tropical of cancer while short rainy occurs October to December when ITCZ moves from equator to tropical of Capricorn [24]. Maximum amount of water normally occurs during long rainy season whereas minimum occurs in dry season (July-September). January to February is a period of warm weather with temperature ranging from 32 to 35 ^{o}C while July to August is a cold period with temperature ranging from 14 to 18 ^{o}C [25].

METHODOLOGY

Sediment core was sampled undisturbedly at the centre of Nyumba ya Mungu reservoir on 26 October, 2014. Local boat was used to reach the centre of the reservoir (Plate 1). The core of about 40 cm was cut into slice of 1 cm thickness and each was kept in a separate plastic bag. Wet mass of each sediment samples was measured then dried at 40 ^{o}C in laboratory located at Nelson Mandera African Institution of Science and Technology. Thereafter, dried sediment samples were transported to East China Normal University in the State Key Laboratory of Estuarine and Coastal Research for further preparation and analysis.

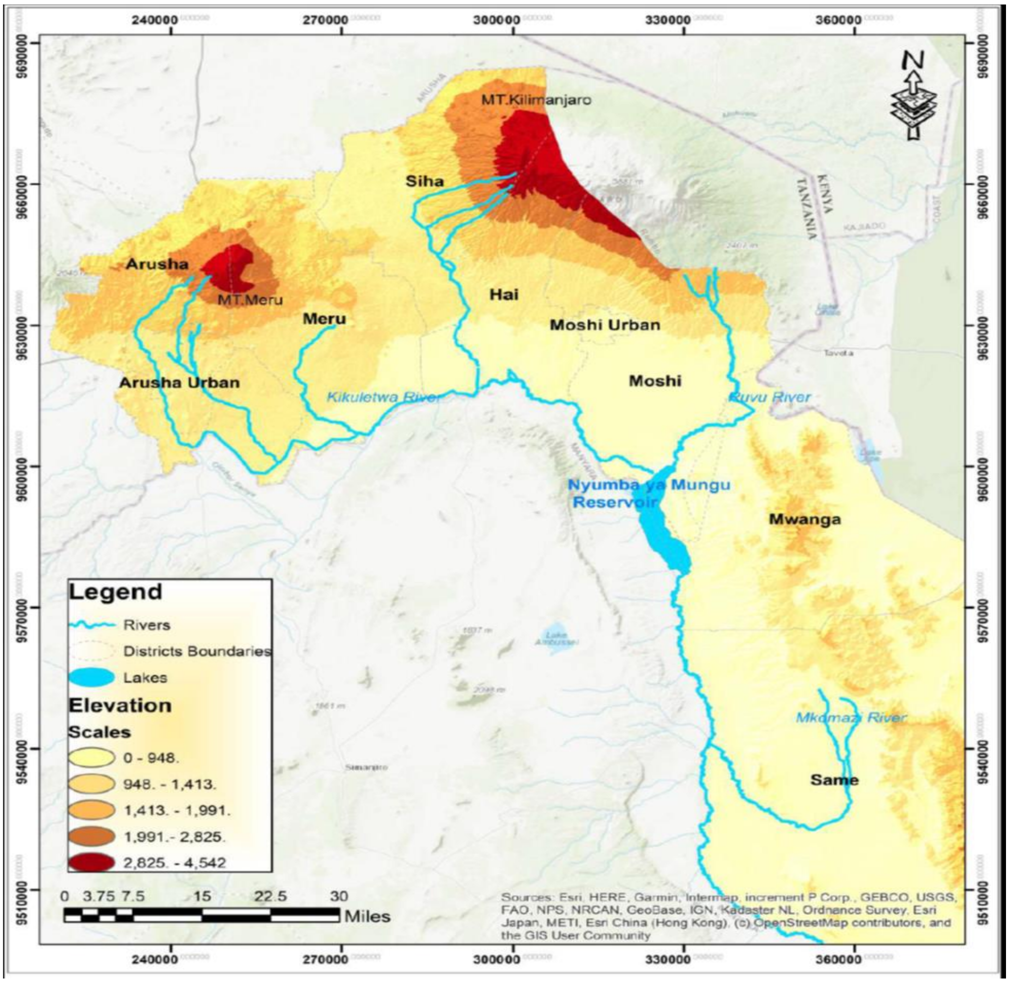

Fig. (1): study area indicating location of Nyumba ya Mungu Reservoir on the slope of Mt. Kilimanjaro

(a) (b)

Plate (1): Sampling of sediment core from Nyumba ya Mungu Reservoir, (a) local boat was used to sample at the centre of the reservoir with core sampler, (b) sediment slice of 1 cm thickness was cut and each kept in plastic bag.

In the State Key Laboratory dried sediment were grounded to fine size and sealed in holders allowed to stabilize for 3 weeks. HPGe γ spectrometer (GWL-120210S) was used to measure ^{210}Pb using gamma emissions at 46.5 keV while gamma emissions at 661 keV were used to determine ^{137}Cs. The experimental error was less than 10% hence the results was within acceptable range.

Radionucleide elements lead and caesium (^{210}Pb and ^{137}Cs) were used to estimate rate of sedimentation in Nyumba ya Mungu reservoir. Sedimentation rate was estimated by considering naturally occurring of ^{210}Pb produced from radon-222. In the sediments/soils some ^{222}Rn escapes to the atmosphere as gases thereafter decay to release 210Pb which later fall as dry fall or as a results of precipitation as wet fall [26]. On the other hand, ^{137}Cs is mostly considered as fall-out from nuclear bombs testing [26]. Most of ^{137}Cs in the soil results from nuclear bombs testing which took place between 1952 and 1964. The peak of ^{137}Cs in most areas occurred in 1964 which can be used as marker to date sedimentation rate in a given area [27]. In the atmosphere ^{137}Cs which comes from nuclear bombs can attach to aerosols and derived to the land surface through rainfall [28]. On the land surface ^{137}Cs can attach in the particulates and be eroded by surface runoff to the rivers and lakes. Graph of radioactivity against depth can be used to estimate rate of deposition. Peak of the activity can be considered to occur at 1964 and the remaining depth be taken as the materials deposited after 1964 [28].

Application of ^{210}Pb to determine rate of sedimentation was done by Constant-Initial-Concentration (CIC) [29]. Flux of ^{210}Pb was assumed to be constant under CIC [29, 30].

RESULTS AND DISCUSSION

Rate of sedimentation in Nyumba ya Mungu reservoir

^{238}U has half-life of 4.5×10^9 years; in the soil uranium can decay to radon [31]. Part of radon can remains in soil while other part can escape to the atmosphere. ^{222}Rn has half-life of 3.88 days; decay of radon can release ^{210}Pb. Excess ^{210}Pb is produced from decay of Rn in the atmosphere whereas decay of Rn in the soil release supported ^{210}Pb [32]. Additional of ^{210}Pb is considered to be excess to the normal amount of Pb supplied by the decay of ^{226}Ra, resulting from nuclear emission [33]. Excess ^{210}Pb can be delivered to the soil, rivers and lakes in similar way to that of ^{137}Cs [31].

Generally, figure 2 shows ^{210}Pb and ^{137}Cs excess increased from bottom to the top of the sediment core. The increase was contributed by nuclear bomb testing in recent years compared to the natural deposit/formation of those radionuclides. The variation in the excess might also be associated with disturbance contributed by anthropogenic activities or scavenging caused by micro-organisms before and within the reservoir. It was observed that sediment disturbances caused by organisms or precipitation can influence dating sediment [34]. Therefore, care should be taken when sampling not to disturb and sampling should take place in undisturbed sediment.

Figure 2a shows distribution of excess ^{210}Pb versus the depth in the reservoir. Each Pb excess is stipulated with horizontal error bars representing the standard deviation. By using Constant-Initial-Concentration (CIC) model rate of sedimentation was estimated from 13 cm depth by assuming that below this level rate of sedimentation was uniform (Fig. 2a). Adopting the formula developed in Lubis [29], the following procedure was followed

$$C= C(o)e^{-kt} \ldots\ldots\ldots\ldots \quad \ldots\ldots\ldots \textbf{(1)}$$

Where C is total excess, C(o) is excess ^{210}Pb, k=ln2/half-life of Pb

Therefore rate of sedimentation was estimated from

$$t=\frac{1}{k}\ln\frac{C(o)}{C}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(2)}$$

The estimate showed that rate of sedimentation was 0.24 cm/year.

It is wisely to use more than one radionuclide to estimate sedimentation rate. Therefore, this study used ^{137}Cs to verify sedimentation obtained from ^{210}Pb. Figure 2b define peak for ^{137}Cs activity occurred at 33 cm; when assuming the peak occurred due to the testing of nuclear weapons in 1964 the estimate gave sedimentation rate of 0.66 cm/year [27]. Recent ^{137}Cs peak occurred at 13 cm depth which can be associated with Chernobyl accident 1986-87 [34]. Estimate from this peak gave sedimentation rate of 0.46 cm/year.

Normally sedimentation rate is not uniform due to the variation in deposition rate of biomass, chemical and other inflow materials associated with weather condition and anthropogenic activities. According to this results rate of deposition was higher when the dam was constructed in 1965 to 1986 about 0.66 cm/year, thereafter the rate decreased to 0.46 cm/year in recent years. The decrease in sedimentation in recent years appears to be reasonable as the campaign of planting trees increases in upstream to decrease erosion. Sedimentation rate estimated from ^{210}Pb was comparable to that of ^{137}Cs. Therefore, results from all tracers showed that rate of sedimentation in PRB ranged from 0.21 cm/year to 0.65 cm/year.

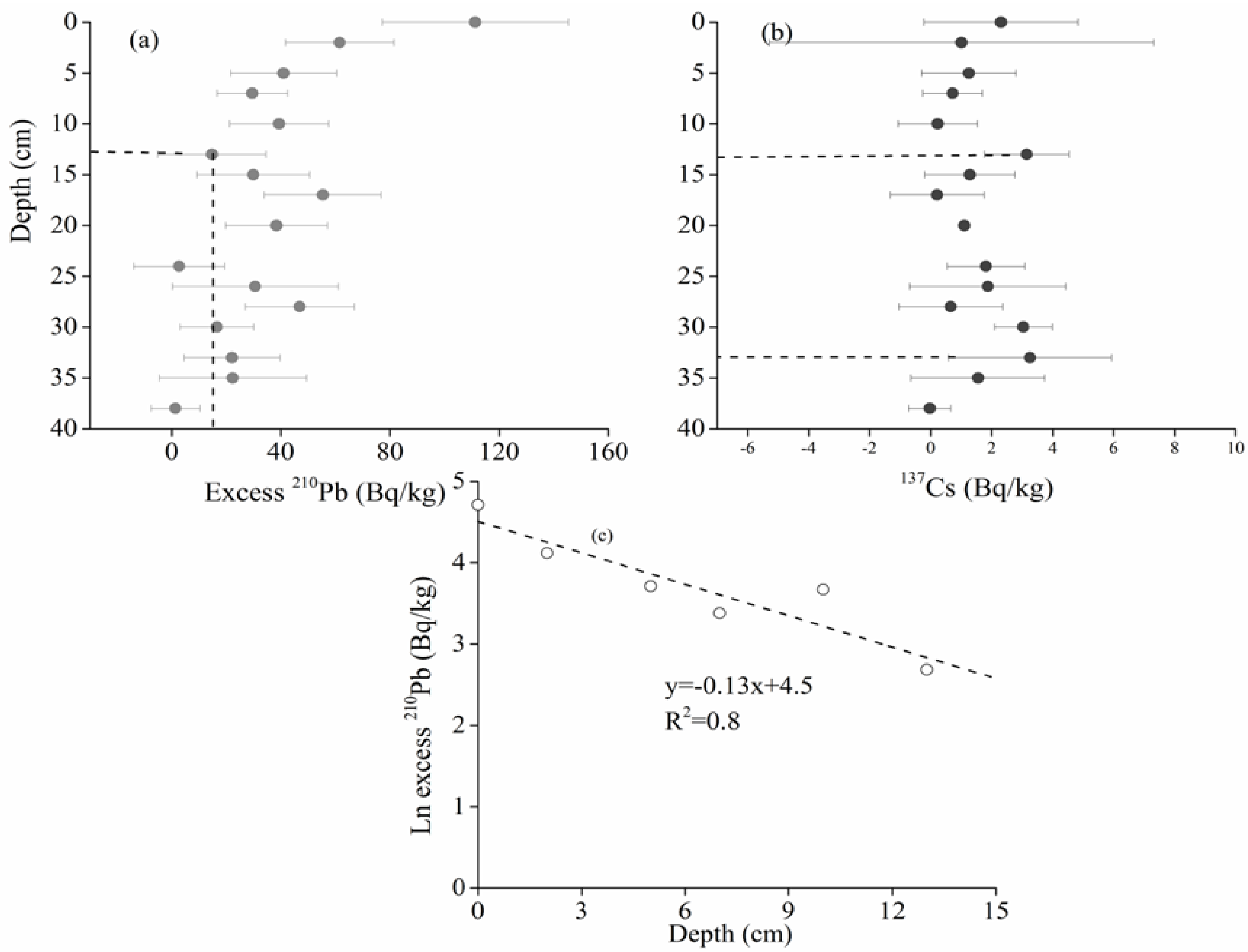

Fig. (2): Variation of excess ^{210}Pb and ^{137}Cs activity, (a) rate of sedimentation was taken from 13 cm depth and detail was indicated in (c); (b) showed peak of ^{173}Cs occurred on 33 cm and 13 cm depth.

Table (1): Comparison of sedimentation rate in different water bodies

Lake Van, eastern Turkey [35].	Wham Brake reservoir in North Louisiana [36]	Baltic sea [37]	Hong Kong Harbor [38]	Lake Naivashi-Kenya [39]	Nyumba ya Mungu (this study)
0.3-0.7 mm/year	0.05 cm yr -1	2.5-6.5 mm/year.	4.3-7.8 cm/year	0.93-1.3 cm/year	0.21-0.65 cm/year

The ^{210}Pb and ^{137}Cs can be used in dating sediments of recent years. Determining the rate of sedimentation needs accurate measurement of ^{210}Pb in a sediment samples. Undisturbed sediment cores with uniform textures are the needed samples to give accurate results as Pb is trace elements which can be scavenged by organic matter. Mobilized Pb can also be re-distributed in different season on young sediments giving significant errors in estimating sedimentation rate. Furthermore, it was observed that in Nyumba ya Mungu Reservoir rate of sedimentation was varying from one depth to another therefore it is recommended to have more than one core thereafter consider the average.

Comparison of sedimentation rate in different regions

As pointed in paragraph 5 rate of sedimentation differ from one place to another depending on human activities, climate of the area, topographical features and soil type. Hong Kong harbor with more anthropogenic activities was observed to have high rate of sedimentation compared to Baltic Sea (Table 1). Lake Naivashi and Nyumba ya Mungu Reservoir both are located in tropical region but sedimentation was higher in Naivashi compared to nyumba ya Mungu possibly human activities and soil types can play part to increase sedimentation in Naivashi.

CONCLUSION

The radionuclides' activity of ^{210}Pb and ^{137}Cs was measured in order to determine sedimentation rate in Nyumba ya Mungu reservoir. ^{137}Cs gave comparable sedimentation rate to that of ^{210}Pb, which call for researchers to use other methods to verify sedimentation rate in the reservoir. Comparing to other data elsewhere, rate of sedimentation in Nyumba ya Mungu reservoir was less than that of Lake Naivash in Kenya as both are located in tropical region characterized by high amount of temperature and rainfall. Rate of sedimentation in Nyumba ya Mungu was higher than Wham Brake reservoir in North Louisiana and Lake Van located in eastern Turkey.

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