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Assessment of Sedimentation Status of Ruiru Reservoir, Central Kenya

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Abstract Reservoir sedimentation can adversely affect the storage capacity of water bodies; reduce flood attenuation, change water quality, damage valves and conduits amongst others. This study investigated sedimentation rate in Ruiru reservoir as a measure for monitoring water resource management using capacity survey method. Water depth was measured using a transducer fitted on the side of the boat which also recorded corresponding geographic positions with an inbuilt GPS receiver. About 5000 points covering approximately 36 hectare of the water surface were surveyed. A total of eleven sediment sampling points were identified in the reservoir in which five were strategically selected at location near entry from respective streams. The depth of sediments, which relate to the quantity of sediment deposition from the streams ranged between 600 mm and 2100 mm. Ruiru stream demonstrated the highest level of sediment influx into the dam while Ngeteti stream had the least. The reservoir volume was calculated to be 2,632,347m^3 and estimate volume of the sediments 389,245 m^3, which is a 13.1% storage capacity loss. A related recent study noted storage capacity loss of 11%, which shows that the reservoir has lost about 11-14% of its storage capacity in 65 years. Results further showed that the Area Specific Sediment Yield (ASY) was 38.84 Mg ha^{-1} y^{-1}, which is higher than the tolerable soil loss of 2 to 18 Mg ha^{-1} y^{-1} for the tropics, but is within the range of 10 - 200 Mg ha^{-1} y^{-1} typical of savanna ecosystems. These findings are useful to water resource managers because they can help in computing the useful life of a reservoir.

Keywords: *reservoir sedimentation, area specific sediment yield, reservoir volume*

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1. Introduction

Throughout the world, several million ponds are constructed for various purposes including irrigation, water supply or flood control [1]. In many of these ponds, sediment deposition from eroded soil can be observed. Soil erosion is therefore a serious problem worldwide which has high economic and environmental impacts because of its extent, magnitude, rate, and associated complex processes [2]. The erosion at times is attributed to anthropogenic activities in the upstream that are in turn associated with tremendous pressure on the ecosystem and over exploitation of natural resources [3]. This further leads to air, water, soil pollution and loss of biodiversity.

Deposits of eroded soil may cause infrastructural damages such as blocking drains, reduced capacity and life of water bodies, damage to roads, power lines, waterways and distorted aquatic habitats [4]. This therefore emphasizes the importance of long term monitoring of rates of reservoir sedimentation and sediment export from catchments. The monitoring helps in understanding the impact of climate and land use changes on sediment dynamics [5] and observance of possible responses of catchments to future climate and land use changes. However, Measurement of sediment is a complex task requiring an integration of various tools and methods. Traditionally, sediment sampling techniques in rivers were mostly limited to suspended sediment load. As a result, analysis of total sediment yield was underestimated [6]. A number of techniques can now be employed to monitor the total sediment yield i.e. by continuously measuring runoff and calculating sediment discharge using sediment-rating curves; by simultaneously measuring both runoff and sediment concentration using sediment traps; by measuring sediment deposition rates in lakes, reservoirs or small ponds [7] amongst others. Use of sediment-rating curves, has a limitation since sediment-rating curves can vary substantially for different rivers over time and also, hysteresis effects are neglected [8,9]. Simultaneous measurement of runoff and sediment concentration is more accurate but requires much effort and is relatively expensive to carry out [10]. Measuring sediment deposition rates in reservoirs is more practical since it uses existing infrastructure and only periodic surveys need be conducted. To measure the amount and distribution of the sediments, bathymetric (below water) survey is currently the best method to use, [11] because sediments accumulation is not easily visible below the depths of a reservoir.

1.1. Measuring Sediment Deposition Rates in Reservoirs.

One of the most common method for measurement of sediment deposition rates involves the use of core tubes that collect sediment samples from the bottom of the reservoir [12]. This method is capable of providing as much information on sediment delivery to river channels as continuous measurements of suspended sediment concentrations do. For every sampling point, analysis of sediment cores taken from the reservoir allows identification of multiple depositional events. The methodology allows measurement of total sediment yield on the reservoir bed. Since this method uses existing infrastructure and require little time, many reservoirs can be surveyed over a short period, thus, providing information on the spatial variation in Sediment Yield (SY) at regional scales [7]. According to [7], the topography of deposited sediment in the reservoir can be measured at regular time intervals. A comparison between two successive bathymetric surveys may yield the sediment deposition volume for the specific period.

1.2. Limitations of Measuring Sediment Deposition Rates in Reservoirs

The methodology requires at least three parameters to be measured or predicted, [13]. First, sediment accretion volumes need to be measured for a given time span. Secondly, these sediment volumes need to be converted to sediment masses using representative values of the dry bulk density of the sediment deposits and, finally, the sediment Trap Efficiency (TE) of the pond needs to be assessed. Where ASY is required, catchment area has to be determined. For reservoirs whose sediment deposition rates/sediment volumes are known, representative values for bulk density and TE are needed. The accuracy of the calculated SY value will therefore depend not only on the accuracy of the calculation of Sediment Volume (SV), but also on that of bulk density and TE, [14]. The accuracy of the calculated SV will depend on both the accuracy of the topographic survey and that of the volume computation [15]. Estimation of each parameter (SV, TE, SY, bulk density) is subject to important limitations that are unique to each. During survey, it is important that well-fixed checkpoints are used, which are not subject to minor vertical or lateral displacements between two successive surveys. Consequently, total error on SV will depend on the rate of sediment deposition and the pond area [16]. Large deposition volumes in a small pond (i.e. with high vertical accretion rates) are determined with a greater accuracy than small deposition volumes in a large pond, [17]. For consistent and accurate results, the surface of the deposited sediments in the pond needs to be surveyed at regular time interval [18].

2. Materials and Method

2.1. Description of the Study Area

Ruiru dam is located near Githunguri town in Kiambu County, Kenya. The basin that drains into the reservoir lies between 36°34' E and 37°11' E, and between 0°50' S and 1°11' N, (Figure 1).

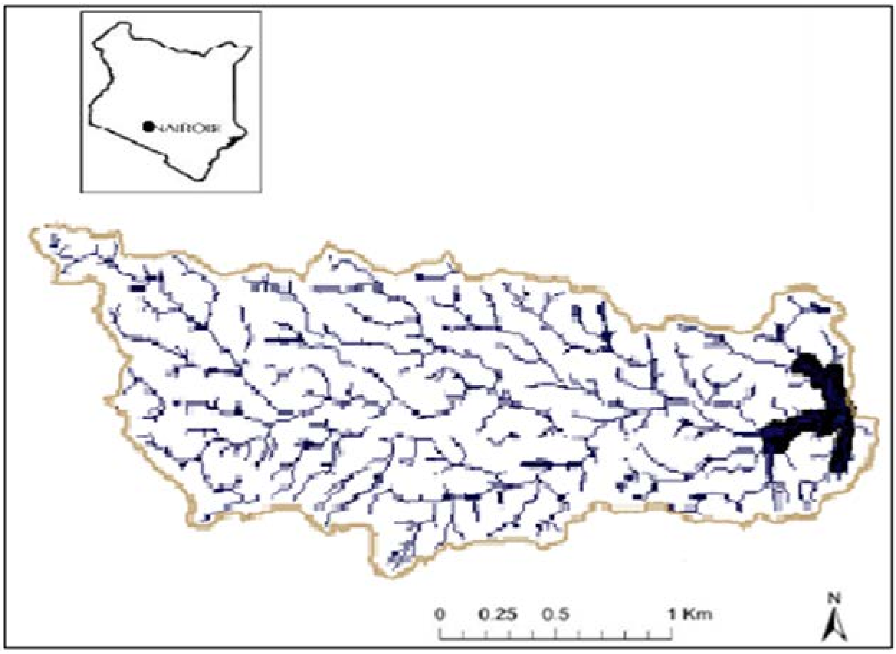

Figure 1. Location of Ruiru dam in Kenya

The upstream catchment falls within the upper Tana River basin which is fundamental in influencing the ecosystem downstream [19]. This area is a Tea – Dairy Zone with a fully long cropping season [20]. According to

[20], average annual rainfall is between 1300 - 1500 mm. The reliability of rainfall during the first rainy season (March – May) and the second rainy season (October – December) is between 700 – 850 mm and 250 - 470 mm, respectively. The current actual land use activities in this Subzone involve mainly the growing of tea, food crops, vegetables and fruits. Pure and improved crosses of dairy cattle, mainly put under zero grazing, dominate livestock keeping enterprises and majority of farmers apply organic manure to their food crops. The dominant soils are well drained, extremely deep, dark reddish brown to dark brown humic Nitosols [20]. The soil and water conservation measures observed in this Subzone included: Fanyajuu terraces, agroforestry trees planted within farms, especially Calliandracalothyrsus, cut-off drains and grass strips [20]. The rivers that drain into the reservoir are Ngeteti, Kaminditi, Waing'ere, Ruiru, Kibathithi 1, Kibathithi 2, Kimaiti and Kanyiriri.

2.2. Bathymetric Survey

The shorelines were digitized from Google earth images using ArcMap, projected to Universal Transverse Mercator (UTM) and loaded onto the fish finder dashboard mounted on the boat. The navigation software displayed the survey lines in which the boat was driven along. The survey was carried out in predetermined survey lines which were set at about 10 m apart. The spacing was able to provide adequate spatial coverage of the reservoir surface. The depth of water was measured with a transducer (the depth sounder) fitted on the side of the boat. The transducer also recorded the respective geographic positions of each water depth with an inbuilt GPS receiver. About 5000 points covering about 36 hectare of the water surface were surveyed, see figure 2 below.

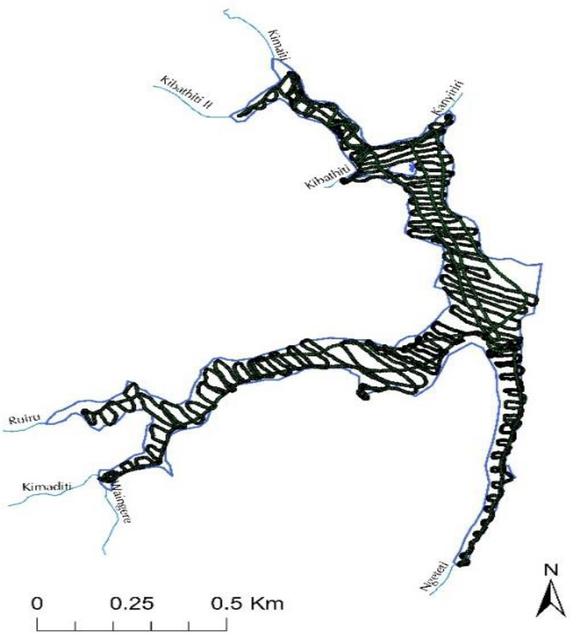

Figure 2. Survey lines and GPS points.

2.3. Sediment Sampling

Eleven sediment sampling points were strategically selected, (Figure 3).

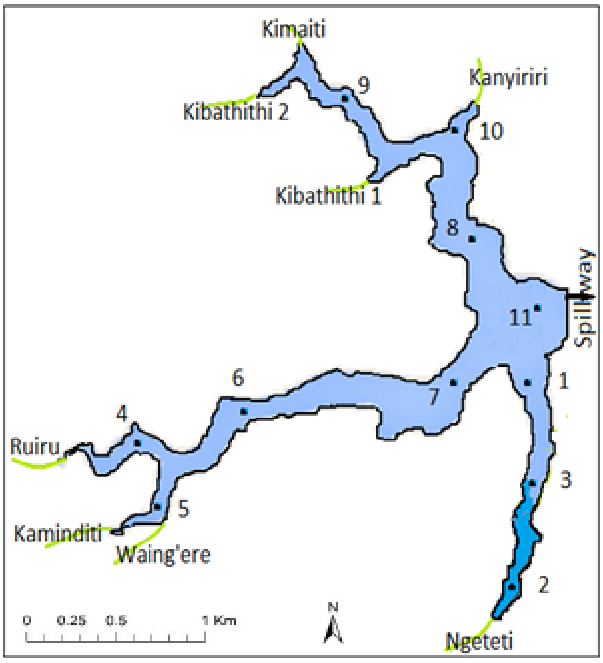

Figure 3. Sediment sampling points

Five of the eleven points were selected near entry points to the main streams to the reservoir. The other six points were selected at various representative locations near the middle of the reservoir. Sediment samples were collected by vibrating the coring tube (51 mm diameter) vertically into reservoir bed using the vibro-core coring device. The procedure was similar to one used by [21] in a flood control reservoir in central Texas [22,23]. Once the consolidated material (assumed original bed of the reservoir) was reached the core tube progression was halted and core retrieved using a winch. For every sediment sampling point, water depth was recorded. In the laboratory, the sediment core tubes were split into two along the length and the depth of the sediment in the core tube measured. Samples from each of the split core tube were analyzed for bulk density.

2.4. Determination of Soil Bulk Density (ρb)

To convert the measured SV to sediment mass, dry bulk density of the sediment was used. The dry bulk density of the sediment samples was determined using gravimetric method where equation 1 was used in calculations. For all the samples collected, the bulk density was determined along the depth at an interval of 10 cm.

$$\rho_b = \frac{W_d}{V} \quad (1)$$

Where: ρb = Dry bulk density (Kg m^{-3})
W_d = Weight of oven-dried soil, (kg)
V = Volume of core cylinder, (m3).

2.5. Estimate Sediment Trap Efficiency of Reservoir

In order to determine the average SY from the contributing watersheds, the weight of deposited sediment needs to be adjusted for reservoir sediments [24]. Equation 2 below as proposed by [25] was used to estimate STE of the reservoir.

$$STE = 100\left(1 - \frac{1}{1 + 0.0021D\dfrac{SC}{A}}\right) \qquad (2)$$

Where: SC = reservoir storage capacity (m3)
A = catchment area (km2);
D = A constant with values ranging from 0.046 to 1 and a mean value of 0.1.

The value of STE depends on D which also depends on a reservoir's characteristics [7]. As noted by [25], determining the value of D is complicated hence a mean value of 0.1 was used for this study.

2.6. Determination of Sediment Yield into the Reservoir

The points downloaded from the GIS receiver were analyzed in ArcGIS to generate the reservoir volume while the sampled depths obtained from the core tubes were processed to generate the sediments volume. During the process, respective sets of data were interpolated using Natural Neighbor, which is noted to offer higher accuracy [26]. The sediment and reservoir volumes are very useful in calculating the rate of siltation (RS), Annual sediment yield (SY) and Area specific sediment yield (ASY) [9]. These parameters were calculated as follows:

$$RS = \frac{SV \times \rho b}{Y} \qquad (3)$$

$$SY = 100\frac{SV \times \rho b}{TE \times Y} \qquad (4)$$

$$ASY = \frac{SY}{A} \qquad (5)$$

Where

TE = Trap efficiency
RS = Rate of siltation
SV = Sediment volume
SY = Sediment yield (calculated)
ASY = Area specific sediment yield
A = Catchment area
Y = Age of reservoir
Pb = Dry-bulk density

3. Results

The eleven sampled sediment depths ranged between 600 mm and 2100 mm. Amongst them, the five samples (2,4,5,9 and10) taken near entry point from the streams ranged between 700 mm and 2100 mm as followsin ascending order: Location 2 (near inflow of Ngeteti stream, 700 mm), Location 9 (near inflow of Kibathiti and Kimaiti streams. 110 mm), Location 10 (near inflow of Kanyiriri stream, 150 mm), Location 5 (near inflow of Waing'ere and Kaminditi streams, 170 mm) to Location 4 (near inflow of Ruiru stream, 210 mm).

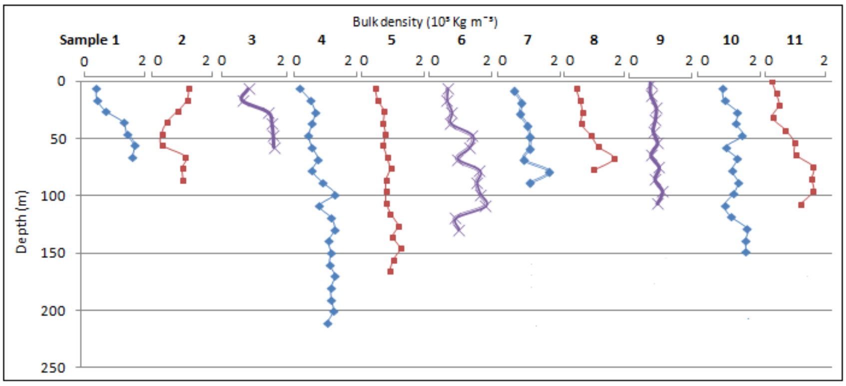

Figure 4. Bulk densities for 11 sediment samples

Average bulk densities for the five sediment samples taken near entry point from the streams ranged between 0.80 * 10^3 kgm^{-3} and 1.22 * 10^3 kgm^{-3} as follows: Kibathiti and Kimaiti (0.80 * 10^3 kgm^{-3}). Ngeteti (0.84 * 10^3 kgm^{-3}), Waing'ere and Kaminditi (0.88 * 10^3 kgm^{-3}), Ruiru (1.16 * 10^3 kgm^{-3}) toKanyiriri (1.22 * 10^3 kgm^{-3}). Bulk densities for all eleven samples ranged between 0.80 * 10^3 kgm^{-3} and 1.22 * 10^3 kgm^{-3}, (Figure 4), with an average of 1.05 * 10^3 kgm^{-3}.

The current reservoir volume was calculated to be 2,632,347 m^3 and estimate volume of the sediments deposits 389,245 m^3. Considering estimate design volume of 2.980,000 m^3 [23], the loss in storage capacity is a 13.1%. A recent related study by [23] noted a volume of 2,564,590 m^3 and storage capacity loss of 11% in July 2015. This shows that the reservoir has lost about 11-14 % of its storage capacity in 65 years. Considering STE of 98%, ASY was found to be 38.84 Mg ha^{-1} y^{-1}.

Figure 5 and Figure 6 below shows the relative water and sediment depths respectively.

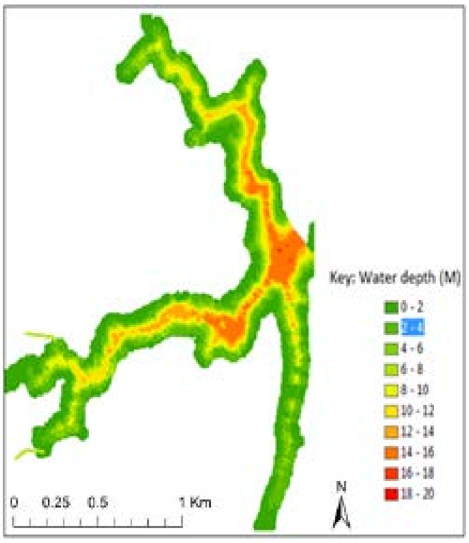

Figure 5. Relative water depths

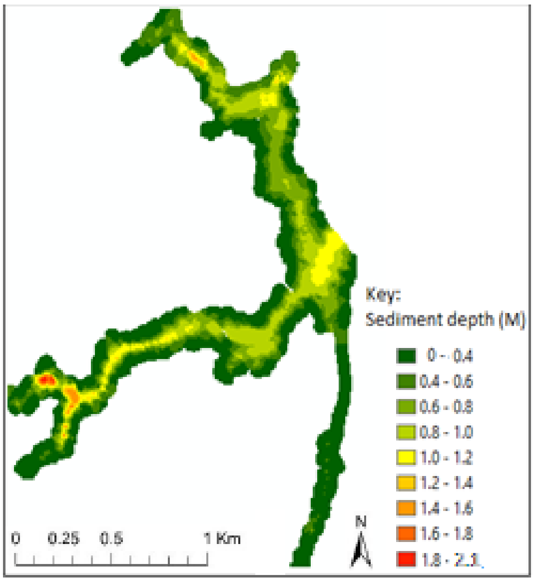

Figure 6. Relative sediment depths

The change in reservoir volume in relation toreservoir depth is demonstrated in Figure 7 below. The curves show surface areas at the different water depths.

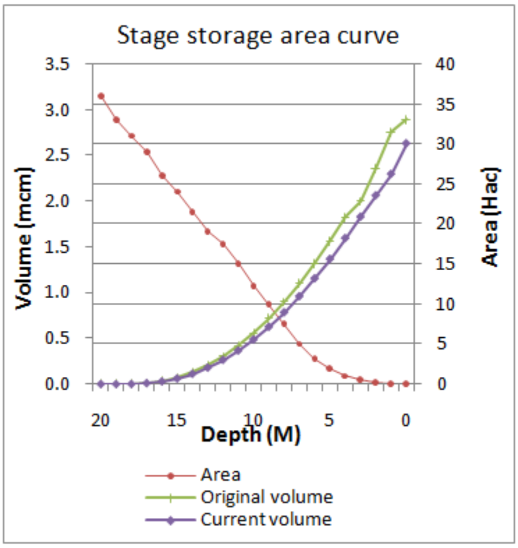

Figure 7. Area-storage capacity curves for Ruiru dam

4. Discussion

The depth of sediment, which relate to the quantity of sediment deposit varied from 2100 mm in Location 4 (near inflow of Ruiru stream) to 600 mm in Location 2 (near inflow of Ngeteti stream). The implication is that Ruiru stream had the highest level of sediment influx into the dam while Ngeteti stream had the least. The high rates of sediment influx from Ruiru stream may be attributed to the long flow distance. The stream has the biggest sub water shed with the longest flow distance, while Ngeteti stream has the least. Other general factors that affect sediment transport include: landscape, land use, soil conservation measures in place, extended dry periods that cause a shift in plant cover and changes in precipitation frequency, duration or intensity, [10].

Dry bulk densities were noted to increase with depth as portrayed in Figure 4 above. The bulk densities within the reservoir also varied significantly. These variations may be brought about by the different kinds of sediment deposited, nature of deposition and compaction levels. In explaining possible causes of such variability, [27] in a similar study conducted in central Belgium observed that the differences can be attributed to spatial hydrologic conditions within the reservoir. As sediment travels through a reservoir, bigger/heavier particle sizes are more likely to be deposited faster (close to the ends of the water body) and the finer sized particles in the deeper part of the water body [28]. The percentage of organic matter content also influences the bulk density [3]. Deposits with high amounts of humus have low dry bulk density values. To assist in deeper understanding of this variability, the sediment cores should be analyzed further for physical and chemical parameters like gain size distribution and Organic Matter content.

Although the percentage loss in storage capacity is not sufficient to cause the reservoir to dry up, the decrease in storage capacity will however affect its function. The ASY of (38.84 Mg ha^{-1} y^{-1}) as obtained in this study was of a similar order of magnitude as those reported in related sedimentation studies by [15]; 17 t ha^{-1} y^{-1}) in Ethiopia and [29]; 21 t ha^{-1} y^{-1}) in Iran. This ASY falls within the range of 10 - 200 t ha^{-1} y^{-1} typical of savanna ecosystems [30]. The ASY rates are however higher than the tolerable soil loss of 2 to 18 t ha^{-1} y^{-1} proposed for tropical soils [30]. Noting that the Global and Africa mean values are 15 and 9 t ha^{-1} y^{-1} respectively [12], ASY of 38.84 t ha^{-1} y^{-1} denotes that the optimum functioning of the reservoir is compromised.

5. Conclusion

The study examined the status of sedimentation in Ruiru reservoir and noted a storage capacity loss of about 11-14%. ASY of 38.84 t ha^{-1} y^{-1}, as noted ranks the study area among regions of the world experiencing high amounts of sediment yield. This high rate of sediment yield implies that the upstream catchment has experienced equivalent high rates of sediment loss which warrants further research on the actual cause and probable remedial strategies.

Continuous conservation and protection of the reservoir is important to sustain availability both in quantity and quality in order to meet the demands of the ever-growing population. The current reduction in reservoir's storage capacity means that the reservoir would have to be used below the intended yields. This implies that the main consumers of the water may experience water shortages and the local basin inhabitants might have to stop dry season farming to maintain water supplies for other critical uses. In addition, reduction in service life of reservoirs result in low internal rate of return and greater loss of money spent for the construction of the reservoir. According to [31], the useful life of the reservoir is terminated when its storage capacity is reduced to 20% of its design capacity. Tim, [11] noted that proper management of sediments can extend the useful life of reservoirs over the long term. Because siltation is not the only factor that can cause reservoirs to dry up, integrated assessment of all factors is necessary. The assessment can start by periodic reservoir sedimentation surveys with an aim of obtaining the trends in reduction in storage capacities.

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