Assessment of Siltation Impact and Mitigation Strategies for Sustaining Storage Capacity in Lwanyo Dam, Tanzania

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ABSTRACT

The ongoing generation, transportation, and deposition of silt in the Lwanyo Dam has significantly reduced the storage capacity of the Lwanyo Reservoir, originally constructed to support irrigation and the surrounding ecosystem. The objective of this paper was to assess the extent of siltation in Lwanyo Dam, evaluate its impact on the dam's storage capacity, and propose measures to mitigate silt accumulation. The upstream catchment area, approximately 39.6 km^2, includes around 128,991 m^2 allocated for rain-fed crop cultivation and 5.89 km^2 for pastoral activities. Frequent overtopping of the reservoir has been observed, largely due to siltation reducing its live storage capacity. In the reservoir trial pits were excavated and assessed, and they indicate that average silt layers range in thickness from 0.54 m to 0.98 m per rainy season. The deposited material consists of a silt layer from 0 to 540 mm, followed by an intermediate clay layer from 540 mm to 3100 mm. The impounded silt depth was measured at 1270 mm, with an estimated siltation volume of 58,349.4644 m^3. The reservoir's original storage capacity of 210,153 m^3 has been reduced by 27.765% due to siltation. The reservoir's structural design inadequately addresses silt management, lacking both silt flushing tunnels and upstream silt check dams. The analysis indicates that storage capacity decreases by 3.085% annually, and if this linear trend continues without any intervention measures, the dam will lose all storage capacity within 24 years. The study recommends urgent measures to mitigate silt accumulation.

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1.0 Introduction

Siltation, also known as sedimentation, is the process by which sediments, primarily composed of sand, silt, and clay, are generated, transported, and accumulated in water bodies (Changotra & Bharti, 2018; Tundu *et al.*, 2018). This accumulation is particularly problematic in instream reservoirs, where silt, an undesirable material, settles at the bottom, reducing the reservoir's storage capacity. The combined effects of upstream anthropogenic activities, such as poor land management, high intensity rainfall, steep terrains, and changes in land use, exacerbate soil erosion, thereby accelerating siltation processes. Given their small particle sizes (sand: 0.05–2.00 mm, silt: 0.002–0.05 mm, and clay: less than 0.002 mm), silt and clay are particularly prone to rapid erosion (Desconhecido, 2012).

Siltation poses several challenges for reservoir management, including reduced storage capacity, frequent dam overtopping, and weakened dam structures due to the induced seismic load effects in seismically active regions. These issues not only shorten the reservoir's service life but also degrade the quality of the stored water (Terêncio *et al.*, 2020). Models such as the Revised Universal Soil Loss Equation (RUSLE), which considers rainfall and overland flow characteristics (Tundu *et al.*, 2018), can be used to figure out how much soil loss from a catchment area leads to dam siltation.

Mitigating the effects of siltation is crucial for maintaining reservoir functionality. Desilting practices are often employed to remove silt and restore the reservoir's live storage capacity (Ghorpade *et al.*, 2018). However, effective silt management must be considered during the design phase of reservoir systems.

The problem addressed in this study is the significant reduction in Lwanyo Dam's storage capacity due to siltation, which threatens its ability to support irrigation and the surrounding ecosystem. The objective of this paper is to assess the extent of siltation in Lwanyo Dam, evaluate its impact on the dam's storage capacity, and propose measures to mitigate silt accumulation. This study aims to provide insights that will aid in making informed decisions for the maintenance and continued operation of Lwanyo Dam, especially in a context where the construction of new large-scale water facilities is declining due to financial and site constraints (Cui & Kuczera, 2023; Ndiritu, 2005). The focus on maximising the efficiency of existing facilities, as highlighted by Katambara (2011), underscores the importance of this research in ensuring the sustainable management of Lwanyo Dam.

1.1 Global Causes and Impacts of Dam Siltation

1.1.1 Causes and Impact of Dam Siltation

Siltation is a complex process influenced by the watershed's sediment yield, sediment transport rate, and deposition mode (Ezugwu, 2013). Dams in tropical regions are more susceptible to siltation compared to those in temperate zones due to intense upstream anthropogenic activities, such as land use changes that lead to deforestation and forest fires. These activities strip the land of protective vegetation, increasing soil vulnerability to erosion, which in turn accelerates the siltation of reservoirs (Terêncio *et al.*, 2020).

Sediment spill, the primary cause of siltation, is shaped by the characteristics of the catchment soil and the topography of the area (Ghorpade *et al.*, 2018). According to Berlijn (2005), siltation affects approximately 40,000 large dams and 300 major dams worldwide. This makes siltation one of the most significant challenges faced by dam managers and operators (Haregeweyn *et al.*, 2012). The deposition of sediment reduces reservoir storage capacity and lifespan, as well as disrupts river flows, necessitating the implementation of mitigation strategies (Eroglu *et al.*, 2010).

1.1.2 Global Overview of Siltation in Hydraulic Structures for Irrigation and Hydropower Dams

Siltation is a global issue that affects the performance and longevity of dams, particularly those constructed for irrigation and hydropower. For example, the Vea Irrigation Dam in Ghana's Bongo District was designed with a maximum storage capacity of 17 million m³ to support agriculture during the dry Harmattan season.

However, after 33 years, its storage capacity was reduced by 26.47% due to siltation, largely driven by conventional tillage practices, continuous grazing upstream, and the effects of high-intensity rainfall (Adongo *et al*., 2014).

A study of 19 large reservoirs in Central Europe, with storage capacities ranging from 148,000 m^3 to 226 million m^3, found that approximately 0.51% of storage capacity is lost annually due to sediment deposition. In Australia, several reservoirs have become fully silted, primarily because their designs did not adequately account for soil erosion and sediment transport processes (Mama & Okafor, 2011). To reclaim silted dams, designated dam flushing tunnels are constructed to wash out the accumulated silt. Depending on factors such as silt type, volume, accessibility, location, and budget, dredging may also be employed as a mechanical method for removing silt from reservoirs. In some instances, the extracted silt is treated before being disposed of downstream (Berlijn, 2005).

The morphological dynamics of a dam's upstream catchment area significantly influence the rate and extent of reservoir siltation. Estimating the quantity of silt accumulation is crucial for predicting the lifespan of a dam's storage capacity. Understanding the silt accumulation coefficient, which is the relationship between the drainage basin flow and the initial reservoir capacity, is important when doing the first steps of silt estimation because it has a direct effect on how long the reservoir lasts (Rdoane & Rdoane, 2005).

For instance, the Revised Universal Soil Loss Equation (RUSLE) model was applied to estimate the impact of sediment accumulation in the Mazowe Catchment in Zimbabwe, particularly for the Chimhanda Dam. The model revealed that the dam's capacity decreased by an average of 6.3% annually, and by 2015, the reservoir's volume had been reduced by 39% (Tundu *et al*., 2018). This highlights the global challenge of siltation, emphasising the need for its consideration during the design phase of dam construction and the importance of environmental conservation upstream.

This study evaluates the siltation of Lwanyo Dam through practical field investigation and characterises the accumulated silt, providing essential insights for the sustainable management of the dam.

1.2 Description of Lwanyo Dam

1.2.1 Location and Climate at Lwanyo Dam

Lwanyo Dam is situated in Mbarali District, Mbeya Region, Tanzania, at the base of the Poroto Mountains (see Figure 1). The dam’s catchment area spans 39.6 square kilometres, with altitudes ranging from 1,350 m to 2,734 m above sea level. The region experiences a range of rainfall between 986 mm and 2,200 mm annually, with a single rainy season from October to May. The majority of rainfall occurs between January and March (Katambara, 2013). Temperatures vary between below 17 °C and above 24 °C, with higher temperatures typically from October to December and lower temperatures from June to August (see Figure 2).

According to local reports, farming activities occur upstream, and detailed modelling is required to assess how these practices contribute to sediment generation, conveyance, and silting.

Structurally, Lwanyo Dam is a gravity dam built of plum concrete, designed to store 210,153 m^3 of water. This capacity aims to enhance water availability for the Ruanda Majenje irrigation scheme, which covers 1,000 hectares. The dam’s design includes a deepest foundation level of 1,348 m, a crest elevation of 1,363 m, and a crest height of 9.28 m.

1.2.2 Geological Characteristics of Lwanyo Dam

The geology around Lwanyo Dam is characterised by metamorphic, sedimentary, and volcanic rock units, which are porous with interconnected pore spaces. This geological feature allows the subsurface flow to be experienced.

Fig 1
Location of the Lwanyo Dam and the Upstream Sub-Catchment

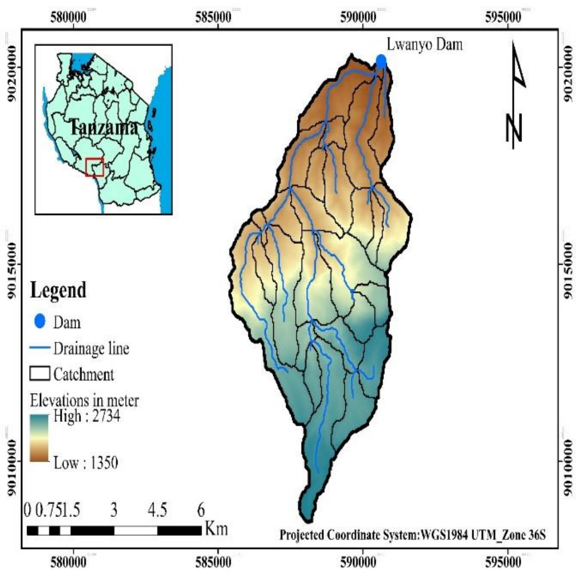
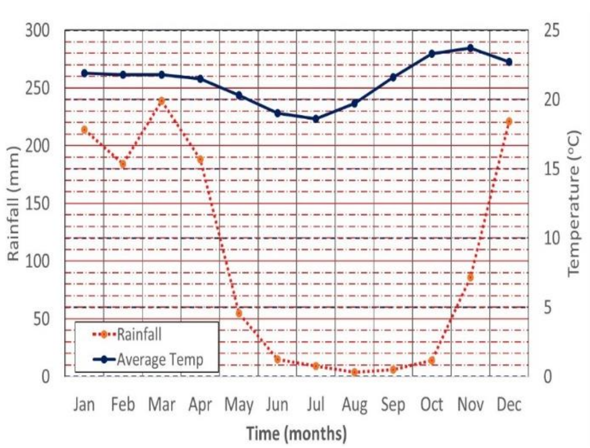


Fig 2
Annual Average Rainfall and Temperature within the Lwanyo Sub-Catchment

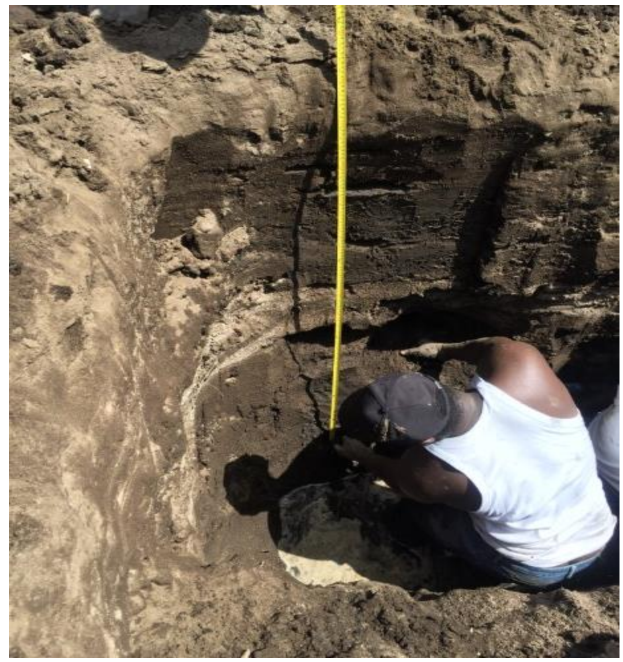


2.0 Materials and Methods

2.1 Estimation of Silt Volume

The volume of silt accumulated at the bottom of the Lwanyo Reservoir was determined through a field investigation. Test pits were excavated to a depth of 3.2 meters, which revealed the original ground. Beyond this depth, undisturbed soil was observed. Figure 3 shows the researcher excavating one of the pits, where the walls were noted to be stable.

Fig 3
Excavation of the Silt to a Depth of 3.2 m



The vertical profile of the silt layer varied according to its characteristics, and the layer thickness was recorded along with the corresponding surface area. The volume of silt (Vi) at each layer's thickness (Hi) was calculated as the product of the average of two successive areas and the layer's thickness. The subscripts 1, 2, … i… n represent the variables (V, H, A) as shown in Figure 4. The volumes are calculated as follows:

$$V_1 = \frac{A_1 + A_2}{2} \times H_1 \quad (1(a))$$

$$V_2 = \frac{A_2 + A_3}{2} \times H_2 \quad (1(b))$$

$$V_i = \frac{A_i + A_{i+1}}{2} \times H_i \quad (1(c))$$

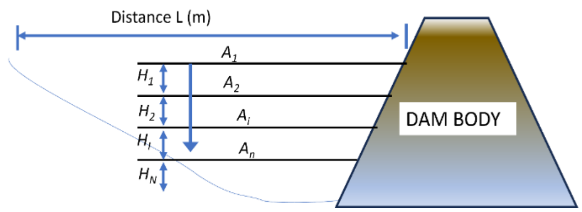
$$V_n = \frac{A_n + A_{n+1}}{2} \times H_n \quad (1(d)$$

The total volume (V) of the silt is given as

$$V = \sum_{I=1}^{n} V_i \quad (2)$$

Fig 4

The Parameters Used in Estimating the Volume of Silt in a Typical Dam



2.2 Determination of Silt Characteristics

Several approaches can be used to determine particle size distribution, including direct measurement, dry and wet sieving, sedimentation, laser granulometry, X-ray serigraphy, and Coulter Counter methods (Blott *et al.*, 2004). In this study, the commonly used sieve analysis, also known as the gradation test, was chosen to assess the particle size distribution of granular materials. This method involves passing the material through a series of sieves with progressively smaller mesh sizes and weighing the amount of material retained on each sieve as a fraction of the total mass. Additionally, the sample materials were classified at each depth to identify their characteristics. The laboratory protocols followed were similar to those described by Onyango *et al.* (2017) for obtaining the physical properties and classification of silt. These included: (a) Sieve analysis (CML Test 1.7: BS 1377: Part 2:1990) and (b) Atterberg limits (CML Test 1.2, 1.3, and 1.4: BS 1377: Part 2:1990).

3.0 Results and Discussions

3.1 Volume Occupied and Area Covered by Silty

The accumulated silt in the reservoir covers a maximum surface area of 16,780 m², extending 78 meters from the dam wall. The maximum silt volume is 5.48 m³, occupying a depth slightly above 9 meters (Figure 5). The current average silt depth is 1,270 mm, with an estimated silt volume of 5.48 m³. Consequently, the dam's storage capacity has already been reduced by 27.8%. This reduction is less significant than the 39% observed in the reservoirs of the Mazowe Catchment in Zimbabwe, as reported by Tunda *et al.* (2018).

Since the project ceased in 2013, the current average silt accumulation rate is 6,483.274 m³/year, resulting in a 3.085% annual reduction in storage capacity. A linear extrapolation of the existing data, assuming no environmental conservation measures are implemented, suggests that the dam will have zero storage capacity by 2046, 24 years from now. A similar extrapolation approach has been applied to reservoirs in Sierra Nevada, northern California, by Snyder *et al.* (2004).

The increase in silt load upstream could also cause the dam wall to fail. To prevent this, the dam requires immediate intervention, including redesigning and implementing a silt flushing system at the dead storage level and constructing silt check dams along the inflow channel. These measures would reduce silt accumulation while also increasing the reservoir's lifespan and live storage capacity. However, caution is necessary, as sediment flushing can negatively impact downstream aquatic life and exacerbate riverbed and bank erosion (Snyder *et al.*, 2004).

A strong linear relationship was found between the area covered and the volume of silt, with a correlation coefficient of 0.987, which means there was a nearly perfect correlation (Figure 6).

Fig 5

Distance, Area and Volume Silt Relationship

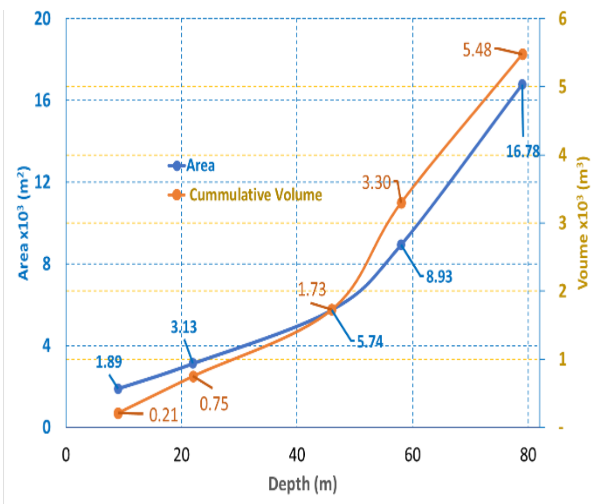
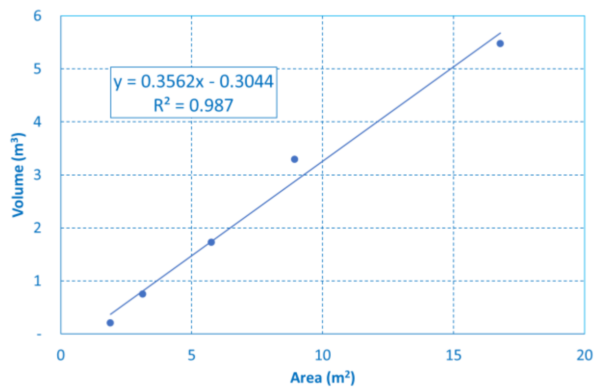


Fig 6

Correlation between Surface Area Covered by Silt to the Volume Occupied by Silt



3.2 Characteristics of the Silt

The analysis indicated that silt and sand are the dominant materials accumulating in the reservoir, with varying thicknesses observed across all sample pits. The silt samples began to be retained at a sieve size of 3.75 mm, and based on classification, the retained soil was identified as sand. Figures 7 and 8 illustrate the grain distribution obtained from the sieve analysis. At depths of 0.0–0.3 m, 0.85–2.5 m, and 2.5–3.1 m, a wide range of particle sizes was observed, indicating the presence of sand grains approximately 0.06 mm in size. In the remaining depths, the majority of grain sizes were around 0.06 mm, with more than 80% passing through the sieve series, showing a narrower range of grain size distribution.

Figuring out how to group each soil depth by the rainy seasons shown by the layers suggests that different amounts of rain led to different erosion patterns, which created silt with different-sized particles, as shown in Figure 8. The rainy seasons and their intensities represent the flow energy required to erode the catchment, with an average silt layer thickness ranging from 542 mm to 987 mm per rainy season. This finding confirms the existence of a complex erosion process, as discussed by Ezugwu (2013).

Fig 7

Grain Size Distribution that was Observed during Sieve Analysis

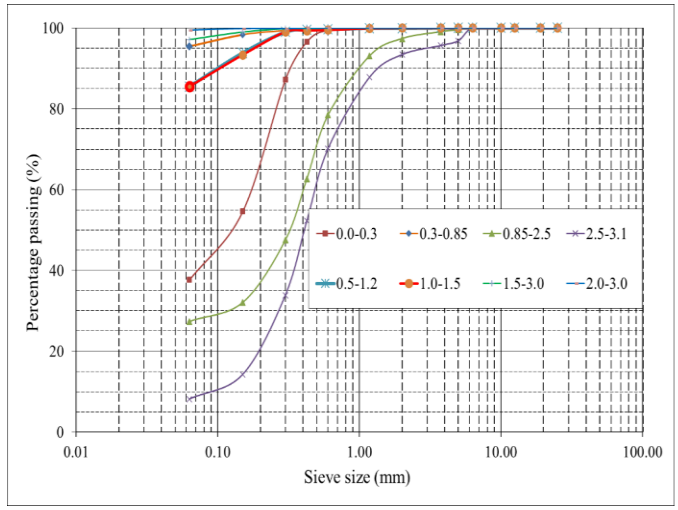
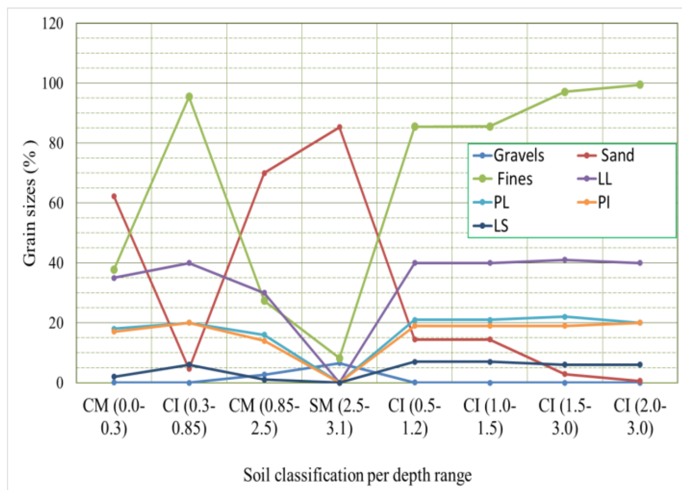


Fig 8

Soil Classification per Depth as Observed During the Excavation



4.0 Conclusion and Recommendations

4.1 Conclusion

The primary objective of this study was to quantify the silt accumulation in Lwanyo Plum Dam, analyse the type of silt material, and propose appropriate measures to mitigate ongoing sedimentation. Deforestation in the Lwanyo Dam catchment area has been identified as the major source of siltation in the reservoir. Human activities, including crop cultivation covering 128,991 m² and pastoralism over 5.89 km^2 within the catchment and near the inflow channels, have significantly impacted the dam's depth.

Currently, an average of 58,349.46 m^3 of silt has accumulated in the reservoir, reducing the dam's capacity by 27.8%. This reduction has shortened the dam's lifespan. The silt material analysis revealed that the predominant sediment is silt with intermediate clay particles. During a single rainy season, silt layers range from approximately 542 mm to 987 mm in thickness. The loam soil in the area is poorly defined, as the deepest excavation revealed it to be light, flowing mud.

4.2 Recommendations

The findings of this study indicate that Lwanyo Dam continues to experience significant siltation, with projections suggesting that in 24 years, the dam may have zero live storage. To address this situation, the following measures are recommended:

1. Preserve the natural condition of the catchment by halting all human activities in the area and implementing afforestation programs.
2. Construct silt check dams along the Mkoji River inflow streams to reduce sediment transport into the reservoir.
3. Implement a safe dam silt flushing system to facilitate the removal of accumulated silt.
4. Initiate the immediate removal of the accumulated silt to restore the dam's capacity.
5. Conduct an intensive study on siltation processes and their impact on dam lifespan, which should be considered in future dam construction projects.

5.0 Funding

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7.0 References

Adamo, N., Al-Ansari, N., Sissakian, V., & Laue, J. (2020). Dam safety: General considerations.

Adongo, T. A., Kugbe, J. X., & Gbedzi, V. D. (2014). Siltation of the reservoir of Vea Irrigation Dam in the Bongo District of the Upper East Region, Ghana. *International Journal of Science and Technology,* 3(12), 12.

Berlijn, R. (2005). Dams and lakes: Problems and possibilities. *Hydro International,* 9(5), 54–57.

Blott, S. J., Croft, D. J., Pye, K., Saye, S. E., & Wilson, H. E. (2004). Particle size analysis by laser diffraction. In *Forensic Geoscience: Principles, Techniques and Applications* (Vol. 232, pp. 63–73). Geological Society of London, Special Publications. https://doi.org/10.1144/GSL.SP.2004.232.01.08

Changotra, S., & Bharti, S. (2018). Impacts of siltation in dams and reservoirs. *Journal of Environmental Science*, 1(2), 7–10.

Charles, J. A., Tedd, P., & Warren, A. (2011). Lessons from historical dam incidents.

Cui, L. J., & Kuczera, G. (2003). Optimizing urban water supply headworks using probabilistic search methods. *Journal of Water Resources Planning and Management,* 129, 380-387. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:5(380)

Desconhecido. (2012). Soils and soil physical properties. *Soil Properties*, 24.

Eroglu, H., Çakır, G., Sivrikaya, F., & Akay, A. E. (2010). Using high-resolution images and elevation data in classifying erosion risks of bare soil areas in the Hatila Valley Natural Protected Area, Turkey. *Stochastic Environmental Research and Risk Assessment,* 24, 699-704. https://doi.org/10.1007/s00477-009-0366-7

Ezugwu, C. (2013). Sediment deposition in Nigerian reservoirs: Impacts and control measures. *Innovative Systems Design and Engineering,* 4(6), 54–62.

Ghorpade, P. R., Chavan, A. R., Kadam, M. H. P., & Patil, S. N. (2018). De-silting artifice for dams. *Journal of Environmental Engineering,* 2(4), 6–9.

Governing, R., Design, D., & Safety, D. (2008). New Mexico Office of the State Engineer Dam Safety Bureau.

Haregeweyn, N., Melesse, B., Tsunekawa, A., Tsubo, M., Meshesha, D., & Balana, B. B.

(2012). Reservoir sedimentation and its mitigating strategies: A case study of Angereb reservoir (NW Ethiopia). *Journal of Soils and Sediments,* 12, 291–305. https://doi.org/10.1007/s11368-011-0441-0

Katambara, Z. (2013). Quantifying rooftop rainwater harvest potential: Case of Mbeya University of Science and Technology in Mbeya, Tanzania. *Engineering,* 5, 816–818. https://doi.org/10.4236/eng.2013.58097

Katambara, Z. (2011). Fuzzy and conceptual-fuzzy modelling of complex river systems with scarce data: Case of Letaba River (PhD thesis). University of Witwatersrand, Johannesburg, South Africa.

Mama, C. N., & Okafor, F. O. (2011). Siltation in reservoirs. *Nigerian Journal of Technology,* 30(1), 85–90.

Ndiritu, J. G. (2005). Maximising water supply system yield subject to multiple reliability constraints via simulation-optimisation. *Water SA,* 31, 423–434. https://doi.org/10.4314/wsa.v31i3.5148

Onyango, M., Katambara, Z., Mnkeni, J., Nassibu, S., Ligwanda, M., & Mwakimi, F. (2017). Evaluation of rice husks stabilized burnt and unburnt blocks. *Journal of Engineering and Technology,* 4(2), 68–73. Mbeya Zonal Irrigation Unit Report. (2008). Dam sites report June 2008 (pp. 1–5).

Rãdoane, M., & Rãdoane, N. (2005). Dams, sediment sources, and reservoir silting in Romania. *Geomorphology,* 71(1–2), 112–125. https://doi.org/10.1016/j.geomorph.2004.02.014

Snyder, N. P., Rubin, D. M., Alpers, C. N., Childs, J. R., Curtis, J. A., Flint, L. E., & Wright, S. A. (2004). Estimating accumulation rates and physical properties of sediment behind a dam: Englebright Lake, Yuba River, northern California. *Water Resources Research,* 40, W11301. https://doi.org/10.1029/2004WR003279

Terêncio, D. P. S., Cortes, R. M. V., Pacheco, F. A. L., Moura, J. P., & Fernandes, L. F. S. (2020). A method for estimating the risk of dam reservoir silting in fire-prone watersheds: A study in Douro River, Portugal. *Water (Switzerland),* 12(11), 1-19. https://doi.org/10.3390/w12113218

Tundu, C., Tumbare, M. J., & Onema, J. M. K. (2018). Sedimentation and its impacts/effects on river systems and reservoir water quality: Case study of Mazowe catchment, Zimbabwe. *Proceedings of the International Association of Hydrological Sciences,* 377(3), 57-66. https://doi.org/10.5194/piahs-377-57-2018