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Application of the RUSLE model to estimate sedimentation in the Lwanyo Reservoir in Mbarali District Mbeya – Tanzania

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ABSTRACT

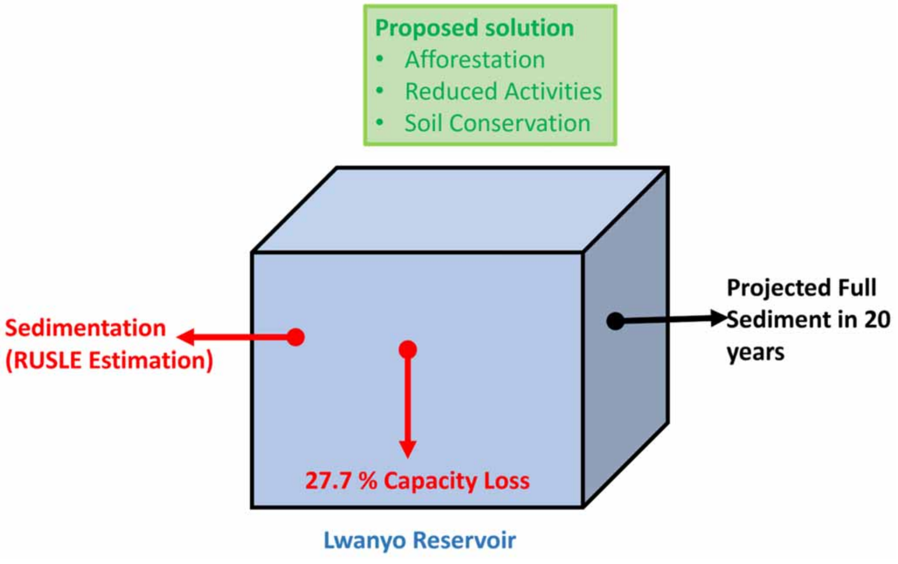
The constant increase in the global population is proportional to the increase in basic human needs associated with environmental degradation. Sedimentation in water bodies poses socio-economic challenges as it lessens the storage capacities. The RUSLE model expresses the effect of sedimentation in the Lwanyo reservoir sub-catchment. Key factors influencing sedimentation include: maximum erosivity factor (R) is 421.39 (MJ mm ha^{-1} h^{-1} yr), the soil erodibility factor (K) is 0.071, the topographic factor (LS) due to catchment topography is 9.086, the vegetation cover and management factor (C) is 0.1045, and the conservation practice factor (P) is 0.14. The RUSLE model estimates soil sediment loss to be 3.977 tonnes/ha/year, as the average annual soil loss for the Lwanyo sub-catchment area is 39.6 km^2. This value indicates that for every hectare, the average annual soil loss is 1.004×10^{-3} tonnes/year, with silt as the dominant soil sediment being eroded. If no intervention measures are implemented, the sediment load could reach 119.31 tonnes over 30 years, reducing the reservoir's storage capacity by 68.177 m^3. Reducing human activity in the catchment and promoting afforestation to mitigate sedimentation can help increase soil stability and reduce erosion.

Key words: afforestation, anthropogenic activities, catchment erosion, reservoir capacity, RUSLE model, sedimentation

HIGHLIGHTS

- Catchment soil loss impacts the water reservoir as it reduces the storage capacity and lessens the life span of the reservoir.
- The RUSLE model estimates the amount of soil loss from the catchment using five input variables from the catchment soil and its topographical nature.
- The effect of catchment soil loss is influenced by human anthropogenic activities.
- Reducing soil loss is based on catchment conservation measures.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Communities depend on water reservoirs to provide water that supports a range of services including the generation of electricity, water supply for domestic uses, to meet irrigation needs, for industrial uses and recreation (Snyder *et al.* 2004; Huang *et al.* 2018). Some of these reservoirs are subject to sedimentation (Wohl & Cenderelli 2000; Huang *et al.* 2018). Sedimentation occurs when soil is eroded from the land surface or stream banks and is transported by runoff and stream flows into water bodies where the reduction in flow velocity deposits the sediment in water bodies like reservoirs (Tundu *et al.* 2018). These hydrological processes are complex (Ezugwu 2013). The sediment yield from a catchment, its transportation and deposition are influenced by a range of factors including topography, rainfall, soil types, vegetation and land use.

Several approaches have been applied to estimate sedimentation in reservoirs. In India, the hydrographic surveys are conducted using echo-sounders, satellite-based global positioning systems and computerized methods to estimate sedimentation. This requires extensive fieldwork, costly equipment and skilled manpower (Goel *et al.* 2002). In contrast, Jain *et al.* (2002) used remotely sensed data to estimate sedimentation in the Bhakra Reservoir in the Himalayan Region. Heidarnejad *et al.* (2006) compared estimates of the sediment volumes that accumulated in the Karaj Reservoir using the hydrometry method (a physical approach) and the hydrograph method (an empirical approach). The sediment volume deposited over 30 years was estimated by the hydrometry method and the hydrograph method to be 416,667 and 406,515 m^3, respectively. The Lwanyo Reservoir in Tanzania, a critical water source for the Ruanda Majenje Irrigation Scheme, was selected for this study due to its significant role in supporting 2,780 people and irrigating 720 ha of farmland. Unlike other reservoirs, Lwanyo faces acute sedimentation challenges, which have drastically reduced its storage capacity, threatening its ability to meet irrigation demands. Its location in a semi-arid region, coupled with its proximity to highly erodible catchment areas, accelerates sediment deposition, making it a compelling case for studying sedimentation dynamics and their impact on reservoir performance. Additionally, the use of empirical sediment modelling approaches, which require fewer resources while producing comparable results, was preferred for this study to effectively assess the reservoir's sedimentation issues (Jahun *et al.* 2015a). Lwanyo's socioeconomic importance and susceptibility to sedimentation, combined with limited studies on similar reservoirs in Tanzania, make it an ideal choice for research on sustainable water resource management (Mkhandi *et al.* 2003; Ngongondo *et al.* 2011).

2. MODEL CLASSIFICATIONS RELATED TO SEDIMENT ESTIMATION

Models can be classified based on their complexity and are composed of empirical, conceptual and process models (Ndiritu & Daniell 1999). Process models are designed to use field-measured values of parameters and are intended to closely represent the processes. Most of these models are distributed in order to represent the physical processes and rely on measured values of parameters (Ndiritu & Daniell 1999). Huang *et al.* (2018)

applied physical-based models where the Buckingham π theorem, hydrodynamic similarity and sediment similarity were applied to estimate sediments in the Wushe Reservoir in Taiwan. However, inadequate data, the complexity of the problem and model imperfections limit the application of physical models in real-world problems (Katambara & Ndiritu 2009).

Conceptual models use simple equations to represent the processes, while empirical models do not represent the processes at all. Conceptual and empirical models are calibrated to obtain the model parameters (Ndiritu & Daniell 1999; Katambara & Ndiritu 2009). Generally, the calibration process involves dividing the observed datasets into two sets: one set for calibration and one set for verification (Ndiritu & Daniell 1999; Jothiprakash & Garg 2009; Katambara & Ndiritu 2010). An acceptable objective function is used to minimize the error. The evaluation of model performance attempts to measure the extent to which the model mimics the process (Moriasi *et al.* 2007; Swilla *et al.* 2024). Empirical models have been widely used to estimate sediment yield including the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1978). Improvements made based on 40 years of research have resulted in an improved version of the model, the Revised USLE (RUSLE), which is capable of incorporating distributed data from GIS, is less costly and has an improved accuracy (Jahun *et al.* 2015b). The RUSLE was adopted for this study.

3. THE RUSLE MODEL

The RUSLE model is a computerized tool for estimating the average annual soil loss and was developed by the Natural Resources Conservation Service (NRCS) within the United States Department of Agriculture (USDA) (Inoue *et al.* 2015). The fundamental equation in the RUSLE model is:

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where A is the computed annual soil loss in tonnes/ha/year, R is the rainfall-runoff erosivity factor, K is a soil erodibility factor, L is the slope length, S is the slope steepness (both LS forms the topographic factor), C is the cover management factor and P is a supporting practices factor (Jahun *et al.* 2015b).

Several studies have developed site – or region-specific functions to estimate these factors, such as Fu *et al.* (2006) who developed an equivalent R factor (Re) for the Inland Pacific Northwest. Renard *et al.* (1997) proposed the erodibility factor, and Moore & Burch (1986) suggested the length of the slope (L) and the steepness of the slope (S). Ghosal & Das Bhattacharya (2020) reviewed the RUSLE model and reported on the variation of rainfall erosivity factor over different climatic zones, the variation of soil erodibility factor over different soil properties, the variation of slope length and steepness factor, the variation of cover management factor and the variation of conservation practice factor. The identification of these variations improved the model's estimation accuracy. The use of the RUSLE model to estimate the sedimentation in the Lwanyo reservoir is described in Section 5.

4. THE STUDY AREA AND DATA

The Lwanyo Dam is located in the Mbeya Region in southwestern Tanzania and serves as a vital water resource for domestic use, irrigation and agricultural activities (Figure 1). The storage capacity of the Lwanyo reservoir was 210,153 m^3. The reservoir's catchment area covers approximately 39.6 km^2 and is characterized by diverse topographical and climatic conditions. The region receives annual rainfall ranging from 986 to 2,200 mm, with significant seasonal variations that influence runoff and sediment transport dynamics. The Mkoji sub-catchment, which is part of the Lwanyo catchment, experiences an average daily river flow of 1 m^3/s during the dry season. Spot discharge measurements fluctuate between 0.06 and 0.3 m^3/s, reflecting the semi-arid nature of the region (Mbeya Zonal Irrigation Report 2008).

The altitude within the catchment ranges from 1,350 to 2,734 meters above sea level, contributing to varied ecological and erosion patterns. The highlands are cooler, with average annual temperatures of approximately 16 °C, while the lowlands are warmer, with temperatures averaging 25 °C. These climatic gradients, coupled with the tropical climate in the Igurusi area, create conditions where erosion and sediment transport are influenced by both rainfall intensity and temperature-driven vegetation cover changes. The valley leading to the reservoir spans about 7,284 m, with steep gradients upstream and flatter terrain closer to the reservoir. This topographical variation accelerates flow velocities in the southern, steeper parts of the catchment, increasing the potential for soil erosion and sediment deposition downstream.

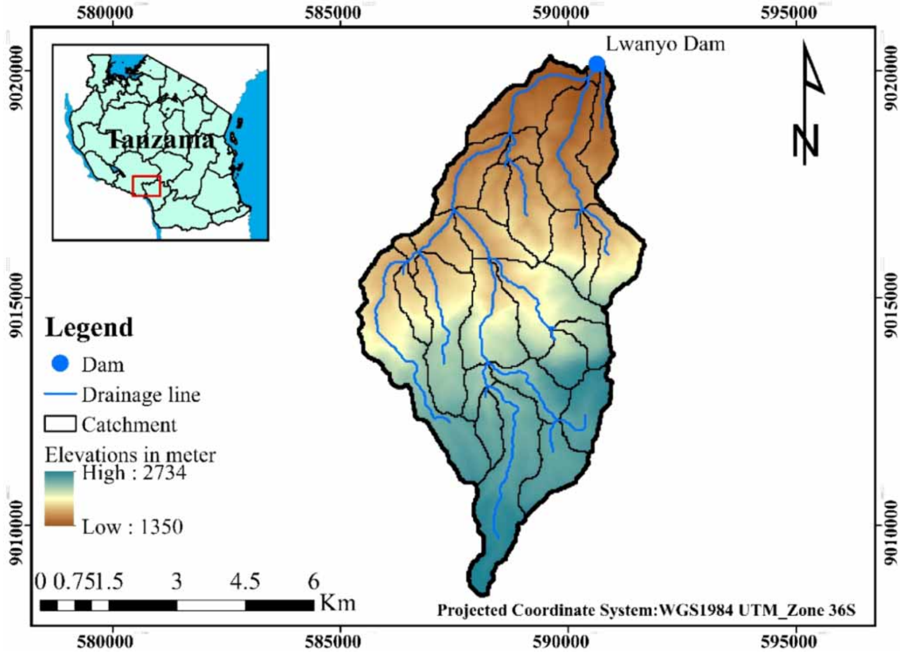


Figure 1 | Location of the Lwanyo Reservoir and its catchment.

The reservoir is situated in a region prone to erosion due to anthropogenic activities such as agricultural land expansion and deforestation, which reduce vegetation cover and exacerbate soil degradation. These factors, combined with the catchment's socioeconomic reliance on the reservoir for irrigating approximately 720 ha of farmland, highlight the critical need for sustainable management practices to mitigate sedimentation and preserve the reservoir's functionality.

Table 1 provides a comprehensive overview of the average monthly temperature (°C) and rainfall (mm) for the Lwanyo Reservoir catchment. The data highlight the climatic variations across months, illustrating both temperature and precipitation patterns critical for understanding the region's hydrology and sedimentation dynamics. The region experiences the highest rainfall in March (239 mm) and December (221 mm), coinciding with a relatively stable average temperature of around 21.8–22.7 °C during these months. These wet months contribute significantly to runoff and erosion, influencing sediment transport into the reservoir. Conversely, the driest months are July and August, with minimal rainfall of 9 and 4 mm, respectively, and cooler temperatures averaging 18.6–19.7 °C. These dry conditions, where there is no rainfall, do not contribute to erosion and sediment transport.

Table 1 | Average monthly temperature and rainfall

Month	Average temperature (°C)	Rainfall (mm)
Jan	21.9	214
Feb	21.8	184
Mar	21.8	239
Apr	21.5	188
May	20.3	55
Jun	19	15
Jul	18.6	9
Aug	19.7	4
Sep	21.6	6
Oct	23.3	14
Nov	23.7	86
Dec	22.7	221

The transitional months, such as May and September, show moderate changes, with rainfall decreasing to 55 and 6 mm, respectively, while temperatures begin to rise, marking shifts between wet and dry seasons. The highest temperatures occur in November (23.7 °C) and October (23.3 °C), indicating a warming trend preceding the onset of the rainy season.

This seasonal variation in temperature and rainfall plays a crucial role in influencing erosion potential, soil stability and the hydrological balance of the reservoir catchment, directly impacting sedimentation rates and water management strategies. Understanding these monthly patterns is essential for planning conservation practices and mitigating sedimentation impacts on the reservoir.

5. APPLICATION OF THE RUSLE MODEL

In order to estimate the sedimentation in the Lwanyo reservoir, it was found necessary to base parameter values on the topographical characteristic of the catchment that drains to the reservoir.

5.1. The rainfall erosivity factor (*R*)

The rainfall erosivity factor considers the kinetic energy of the 30-min rainfall intensity (EI30) to estimate rainfall erosion potential and the total amount is called the rainfall erosion index (Ghosal & Das Bhattacharya 2020). The soil erosivity is affected by the percentage of organic content in the soil mass (Andoh *et al.* 2012). The accurate estimation of the rainfall erosivity factor is degraded by inadequate data; therefore, Fu *et al.* (2006) proposed an equivalent R factor (R_{eq}), as a linear function, given as

$$R_{\mathrm{eq}} = -823.8 + 5.21P_r \tag{2}$$

where R_{eq} is the equivalent R factor for specific climatic conditions and P_r is the annual precipitation in mm. The International Institute of Tropical Agriculture (IITA) also estimates rainfall erosivity using a simple equation based on the maximum annual rainfall (Saptari & Wikantika 2015).

$$R = 0.41 \times (\text{maximum annual rainfall})^{1.09} \tag{3}$$

It is fair to note that the erosivity factor (R) quantifies the potential of rainfall to generate soil erosion based on intensity and duration (Wischmeier & Smith 1978). High erosivity increases the energy of raindrops, leading to significant soil particle detachment and erosion (Ghosal & Das Bhattacharya 2020). It affects sediment transport and contributes to sedimentation in reservoirs, reducing their storage capacity and operational lifespan, as observed in the Lwanyo Reservoir (Moshi *et al.* 2024). Regions with high erosivity are particularly vulnerable to land degradation, especially when combined with deforestation or poor land management practices (Tundu *et al.* 2018). Increased sediment deposition in reservoirs shortens their lifespan and exacerbates flood risks due to heightened runoff rates (Jahun *et al.* 2015b).

5.2. Soil erodibility factor (*K*)

The soil erodibility factor represents the resistance of the soil against erosion due to the impact of a raindrop and the rate and amount of runoff produced for the rainfall impact (Ghosal & Das Bhattacharya 2020). This factor is affected by soil properties such as the percentage of organic matter, sand content, silt soil structure and permeability (Jahun *et al.* 2015b). This study considered the method developed by El-Swaify & Dangler (1976), which uses the grain size distribution of soil (i.e. % sand, % silt and % clay) and the degree of the saturation of the soil. The soil erodibility factor (K) in Mg h MJ^{-1} is given as

$$K = \frac{-0.03970 + 0.00311A_1 + 0.00043A_2 + 0.00185A_3 + 0.00258A_4 - 0.00823A_5}{7.59} \tag{4}$$

where A_1 is the percentage of unstable aggregates $<$0.0250 mm, A_2 is the product of silt (0.002–0.01 mm) and sand (0.1–2 mm), A_3 is the percentage base saturation of the soil, A_4 is the percentage of silt (0.002–0.050 mm) and A_5 is the percentage of sand in the soil (0.1–2 mm).

5.3. The topographic factor (*LS*)

The length of the slope (L) and steepness of the slope (S) are proportional to the erosion. The cumulative runoff increases with an increase in slope and steepness. The model uses four slope length relationships as a function of steepness, rill erosion and inter-rill erosion (Renard & Ferreira 1993). Jahun *et al.* (2015b) suggested a digital elevation model (DEM)-based relationship given as

$$\mathrm{LS} = \left(\text{Flow accumulation} \times \frac{\text{cell size}}{22.13}\right)^{0.4} \left(\frac{\mathrm{Sin(slope)}}{0.0896}\right)^{1.3} \tag{5}$$

Fauzi *et al.* (2024) proposed that the movement or flow of the soil particulate depends on the gradient steepness, which is expressed in percent (%). The mathematical expression of the *LS* factor is calculated using

$$\mathrm{LS} = (x\ (0.0138 + 0.00965g + 0.00138g^2))^{1/2} \tag{6}$$

where x is the gradient length (m) and g is the gradient steepness in %.

5.4. Vegetation cover and management factor (*C*)

This factor represents the influence of soil cover on soil loss, a condition that can be modified by management to minimize erosion. The vegetation cover provides a shield from raindrop impact on the soil surface and dissipates the raindrop energy that would have otherwise impacted the soil surface (Ghosal & Das Bhattacharya 2020). The cover management factor (C) of the RUSLE developed as a function of canopy/surface cover (c) in percentage is as follows:

$$C = 0.6508 - 0.343 \log c \tag{7}$$

where $0 < c < 78.3$.

5.5. Conservation practice factor (*P*)

Tundu *et al.* (2018) report that the conservation factor, P, reflects the control of soil loss by conservation methods. The value depends on whether the area has the maximum conservation or no conservation at all with the value ranging from 0.01 to 1, respectively. Geographic information system (GIS) mapping can be used to estimate the values of the conservation factor.

6. RESULTS AND DISCUSSION

6.1. Calculated values of RUSLE factors

6.1.1. Erosivity factor

Using the annual monthly average rainfall of the Lwanyo catchment suggests that the erosivity factor can provide average rainfall energy for various months within a year. As shown in Equation (2), the rainfall erosivity ranges from 0 (MJ mm ha^{-1} h^{-1} yr) for the dry month to 421.39 (MJ mm ha^{-1} h^{-1} yr). The maximum value is 421.39 (MJ mm ha^{-1} h^{-1} yr) in March and the average value is 110.89 (MJ mm ha^{-1} h^{-1} yr). In Equation (3), the rainfall erosivity factor ranges from 1.68 (MJ mm ha^{-1} h^{-1} yr) to 160.41 (MJ mm ha^{-1} h^{-1} yr). The maximum value is 160.41(MJ mm ha^{-1} h^{-1} yr) in March. The total annual erosivity factor is 1,330.66 (MJ mm ha^{-1} h^{-1} yr) and 960.095 (MJ mm ha^{-1} h^{-1} yr) for Equations (2) and (3), respectively. As a conservative estimate, Equation (2) was used.

6.1.2. Soil erodibility factor (*K*)

The grain size distribution of the soil was estimated from sediment samples collected in the reservoir, as presented in Figure 2. Table 2 shows the *K*-values based on soil texture.

6.1.3. Topographic factor (*LS*)

Figure 3 shows the topography of the catchment upstream of the Lwanyo Dam. The southern part of the catchment is steep and the grade decreases towards the reservoir. The potential for high-flow velocities is greater in the southern areas and velocities decrease as the grades flatten. Applying Equation (6), the *LS* value is 9.086.

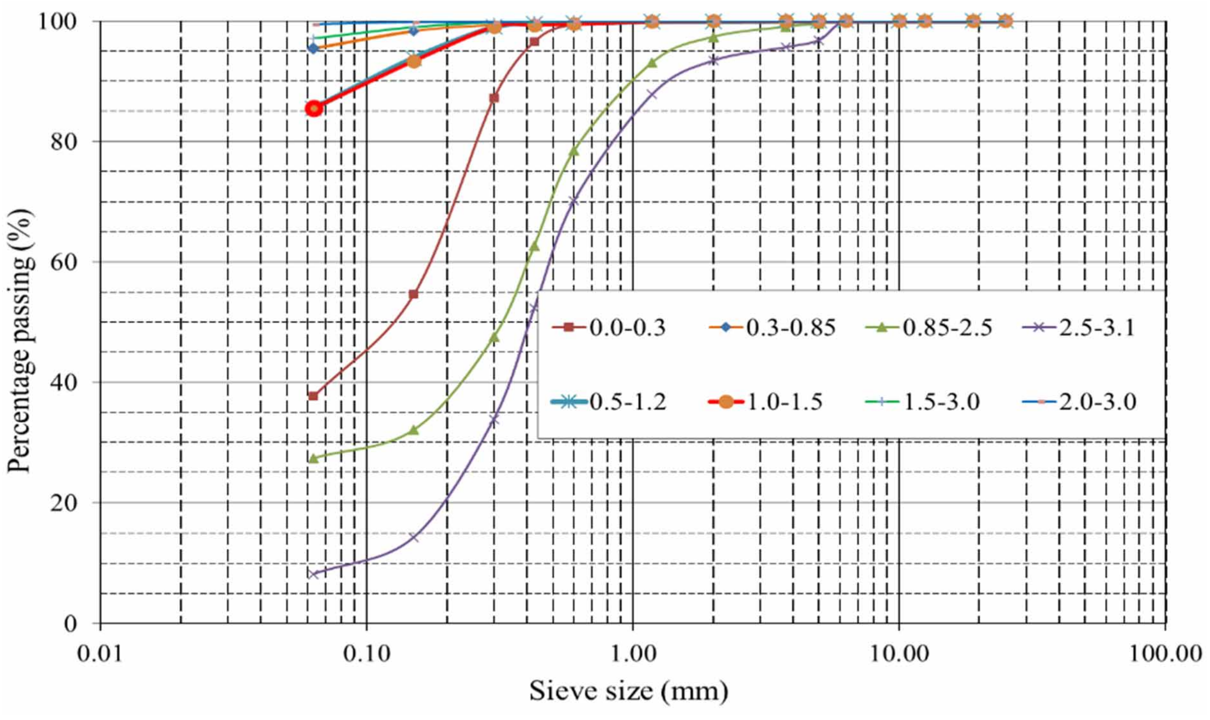


Figure 2 | Grain size distribution for various depth ranges in mm.

Table 2 | Soil loss according to soil texture (Siddique *et al.* 2017)

Soil texture	***S***	***L***	***K*-value**	**Structure**	**Permeability**
Loamy sand	9	22	0.026	Fine granular	Rapid
Silt	9	22	0.071	Blocky	Moderate
Clay	9	22	0.027	Blocky paty massive	Very slow

6.1.4. The vegetation cover and the management factor (*C*)

The vegetation cover and management cover (P) is given in Equation (7). For an average value of c of 39.15%, the value of C is 0.1045.

6.1.5. Conservation practice factor (*P*)

The catchment upstream of the Lwanyo Dam is a conservation area, and the value of the P factor is adopted from Wischmeier & Smith (1978), as reproduced in Table 3. For a slope of 19%, the value of the P factor is 0.14.

6.2. Results of the RUSLE model

Applying the values indicated in Section 6.1.1–6.1.5 into Equation (1) where factors R, K, LS, C and P are 421.39, 0.071, 10.69, 0.1045 and 0.14, respectively, the value is 4.68 tonnes/ha/year. Moshi *et al.* (2024) reported that the volume of sediment deposited in the reservoir over an 8-year period was 58,349 m^3. Based on an assumed sediment porosity of 0.4 and a sediment density of 1,750 kg/m^{3,} this equates to a mass of sediment of 61,266 tonnes.

Averaged over the catchment area of 3,960 ha, this gives an average annual sediment export from the catchment of 1.934 tonnes/ha/year. The difference may be attributed to the silt that flows out during the rainy season since the flows are observed to be turbid.

6.3. Model limitations

The study, which applies the RUSLE model to estimate sedimentation in the Lwanyo Reservoir, highlights several limitations. Key constraints include reliance on average parameter values (e.g., rainfall erosivity and soil erodibility) that may not capture spatial and temporal variability within the catchment (Ghosal & Das Bhattacharya

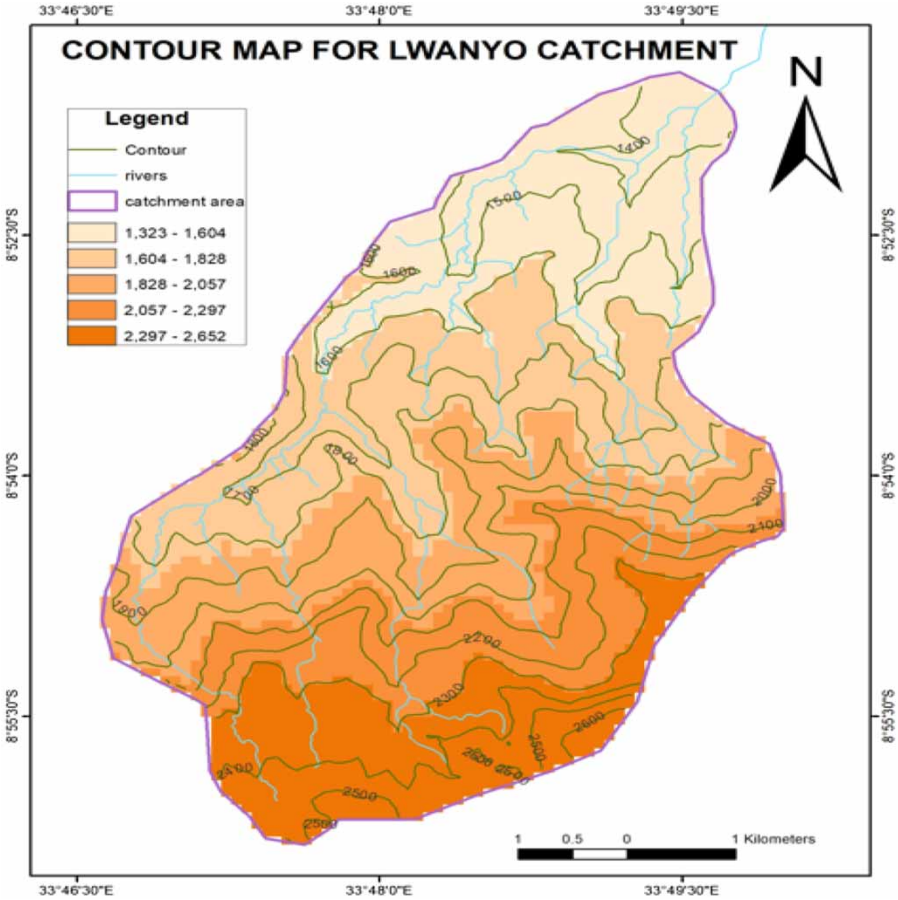


Figure 3 | The topography of the catchment upstream of the Lwanyo Dam.

Table 3 | Land canopy management factor (*P*) (Wischmeier & Smith 1978)

Land-use type	Slope (%)	*P*-factor value
Agricultural land	0–5	0.1
	5–0	0.12
	10–20	0.1^{1}4
	20–30	0.19
	30–50	0.25
	50–100	0.33
Other land	All	1

2020). The model's inability to explicitly simulate complex sediment transport and deposition processes contributes to discrepancies between modelled (3.977 tonnes/ha/year) and observed (1.934 tonnes/ha/year) sedimentation rates (Moshi *et al.* 2024). Data gaps, such as incomplete hydrological records, and simplified assumptions about topography and slope uniformity further reduce accuracy (Renard *et al.* 1997). Additionally, external factors like deforestation, land-use changes and climate variability are not dynamically integrated, limiting the model's predictive utility over time (Tundu *et al.* 2018). These factors suggest a need for complementary methods to enhance sedimentation estimates.

7. CONCLUSIONS

This study aimed to assess whether the RUSLE model provided a rate of sedimentation that matches the rate of sedimentation observed in the Lwanyo Reservoir in the Mbarali District of Tanzania. The Lwanyo reservoir catchment was calculated to experience erosivity factors (R) with values up to 421.39 (MJ mm ha^{-1} h^{-1} yr) in March, a soil erodibility (K) of 0.071, a topographic factor (LS) of 9.086, a vegetation cover and management factor (C) of 0.1045, and a conservation practice factor P of 0.14. The RUSLE Model estimated the annual average soil loss of 3.977 tonnes/ha/year. In comparison, the recorded sedimentation in the reservoir over 8 years, averaged over the catchment area of 3,960 ha, equates to an average annual sediment export from the catchment of 1.934 tonnes/ha/year.

Given that the observed sedimentation has reduced the reservoir capacity by 27.7%, it is estimated that the reservoir would be filled with sediment within a further 20 years in the absence of intervention measures. It is concluded that reducing catchment anthropogenic activities and practising catchment afforestation will reduce soil loss and prolong the life of the reservoir.

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AUTHOR CONTRIBUTIONS

B.M. conceptualized the study and wrote, reviewed, and edited the article. Z.K. wrote, reviewed, and edited the article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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