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Journal of Environmental & Earth Sciences

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ARTICLE

Quantifying Sedimentation and Capacity Loss in Mwimba Reservoir, Malawi: A Baseline Assessment Using Bathymetric and GIS Analysis

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ABSTRACT

Sedimentation in reservoirs is a significant challenge that affects water storage capacity and operational efficiency. This study establishes a baseline sedimentation status for Mwimba Reservoir in Kasungu, Malawi, five years after its commissioning in 2017, using an integrated bathymetric survey and Geographic Information System (GIS) analysis. A bathymetric survey conducted in March 2022 collected depth measurements at 507 points along 23 transects, which were used to construct a Triangulated Irregular Network (TIN) model in ArcGIS for accurate volume calculations. Sediment concentration was determined from seven water samples using the filtration method. The original design volume of 89,200 m³ was compared to the current volume of 72,966 m³, indicating an 18.2% loss in capacity over the five-year period. Statistical analysis using a one-sample T-test confirmed that this reduction is significant ($p = 0.013$). The annual sedimentation rate was estimated at 1.25 tonnes per year, and the reservoir's projected operational life is 27.5 years if no intervention is undertaken. Despite a relatively low sedimentation rate compared to other regional reservoirs, targeted sediment management and further catchment analysis are essential. This study provides critical baseline data for future sediment monitoring, management, and conservation planning for Mwimba Reservoir and similar small water bodies in Sub-Saharan Africa.

***Keywords*:** Sedimentation; Bathymetric Survey; GIS; Reservoir Management; Mwimba Reservoir; Malawi

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ARTICLE INFO

Received: 12 March 2025 | Revised: 25 March 2025 | Accepted: 30 May 2025 | Published Online: 30 June 2025

DOI: https://doi.org/10.30564/jees.v7i7.9061

CITATION

Kumambala, P.G., Steven, R.M., Chipula, G., et al., 2025. Quantifying Sedimentation and Capacity Loss in Mwimba Reservoir, Malawi: A Baseline Assessment Using Bathymetric and GIS Analysis. Journal of Environmental & Earth Sciences. 7(7): 107–117. DOI: https://doi.org/10.30564/jees.v7i7.9061

1. Introduction

Reservoirs are essential for water resource management, supporting functions such as irrigation, flood control, hydropower generation, and potable water supply [1,2]. However, sedimentation is a pervasive challenge that reduces reservoir storage capacity and impairs their ability to meet these demands [3,4]. This issue is particularly critical in regions where reservoirs serve as lifelines for agricultural productivity and domestic water needs, as sediment accumulation can significantly shorten a reservoir's useful life [5].

Sedimentation occurs when sediments settle out of suspension as the velocity of inflowing water decreases upon entering the reservoir, resulting in deposition on the reservoir bed [6]. Studies have shown that the global loss of reservoir capacity due to sedimentation is substantial, with many reservoirs experiencing an annual reduction of 1% to 5% in storage capacity [7–9]. Such losses highlight the importance of understanding sedimentation dynamics to devise effective mitigation measures. Sedimentation is exacerbated by land-use changes, such as deforestation and the expansion of agricultural activities, which increase soil erosion and sediment transport into reservoirs [10–13].

Recent research has focused on quantifying the extent of sedimentation and developing models to predict sediment yield. For example, Endalew and Mulu [14] used bathymetric surveys to assess sedimentation in Ethiopia's Shumburit Reservoir, revealing a 7.5% reduction in capacity over six years due to sediment inflow. Their study demonstrated that combining bathymetric data with GIS analysis can provide precise estimates of sediment distribution and volume loss, a method that is increasingly recommended for sediment management. Similarly, the use of the Soil and Water Assessment Tool (SWAT) for modelling sediment yield has proven effective in identifying sediment-prone sub-basins and guiding management decisions [7,15]. Ayele et al. [15] applied SWAT in the Koga Reservoir, Ethiopia, to predict sediment inflows and assess the impact of catchment characteristics on sediment delivery. Their findings emphasised the role of catchment management in reducing sediment yields, suggesting that targeted interventions, such as reforestation and soil conservation practices, can significantly extend reservoir lifespans.

In Malawi, research on reservoir sedimentation has been limited, with most studies focusing on broader hydrological dynamics rather than detailed sediment assessments [16,17]. Kamtukule [17] emphasised the crucial need for localised sedimentation data to enhance management strategies for small reservoirs. The Mwimba Reservoir in Kasungu, Malawi, commissioned in 2017, has yet to undergo a detailed sedimentation assessment, making this study crucial for establishing baseline data. This gap in research is particularly concerning given the role of Mwimba Reservoir in supporting local agriculture and water supply.

The application of modern techniques such as bathymetric surveys combined with GIS analysis offers a significant improvement over traditional methods for assessing sedimentation. Studies have shown that these tools provide higher precision in mapping sediment distribution, allowing for the creation of detailed Triangulated Irregular Network (TIN) models that represent the reservoir's bed morphology [10,14]. This approach has been used effectively in reservoirs such as Shumburit [14] and Koka [10] in Ethiopia, where it has helped quantify sedimentation rates and guide sediment management practices.

For example, in the Koka Reservoir, sedimentation assessments using bathymetric data revealed that land-use changes upstream led to increased sediment yield, which significantly impacted the reservoir's storage capacity and lifespan [10]. Such studies underscore the importance of integrating spatial analysis and hydrological modelling to understand sediment sources and implement targeted interventions. This is particularly relevant for Mwimba Reservoir, where agricultural activities upstream may contribute to increased sediment load, threatening the reservoir's capacity and sustainability.

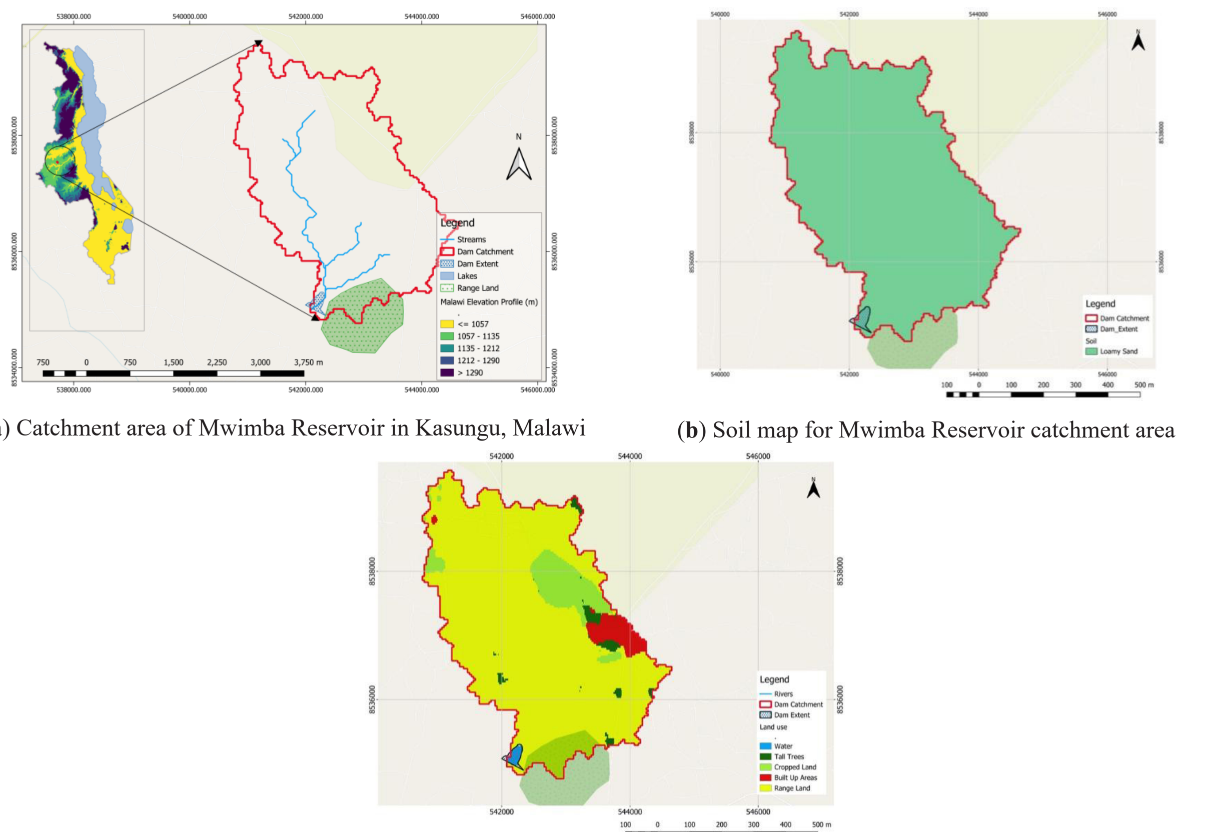
Effective sediment management requires a combination of direct interventions, such as dredging, and upstream catchment management practices, like reforestation and soil conservation [18]. Recent studies have highlighted the benefits of implementing Best Management Practices (BMPs) to reduce sediment inflow into reservoirs. For instance, terraces, contour tillage, and vegetation strips have been shown to reduce sediment yields by up to 60% in erosion-prone areas, as demonstrated in the Gilo watershed study in Ethiopia [18]. In the context of Mwimba Reservoir, such practices could be instrumental in reducing sediment inflow and prolonging the reservoir's useful life. By establishing a baseline sedimentation status using bathymetric surveys and GIS tools, this study aims to inform future management decisions that can enhance the reservoir's sustainability and support the region's agricultural productivity. The specific objectives of this study are to (a) determine the current volume of Mwimba Reservoir, (b) estimate the rate of sediment accumulation since the reservoir's commissioning, and (c) analyse the implications of sedimentation on its operational life. The findings provide essential data for future sediment management in Mwimba and offer insights that could be applied to other small reservoirs in Malawi and similar contexts across Sub-Saharan Africa.

2. Materials and Methods

This study employed a combination of bathymetric surveys and Geographic Information System (GIS) analysis to assess the sedimentation status and storage capacity of Mwimba Reservoir in Kasungu, Malawi. These methods were chosen for their precision and ability to provide detailed spatial data on sediment accumulation, which is critical for effective reservoir management [6,19]. Bathymetric surveys have consistently been shown to provide reliable, direct measurements of depth and sedimentation, while GIS analysis enables the accurate mapping of sediment distribution [20].

2.1. Study Area

Mwimba Reservoir is located at 13°15′0″ S and 33°23′15″ E at an elevation of 1068 meters above sea level in Kasungu district, Malawi [**Figure 1a**]. The reservoir's catchment area covers approximately 9.8 km² and is characterized by two seasonal streams that flow into the Bua River. The surrounding area encompasses agricultural activities spanning over 100 hectares upstream, as well as villages and conservation efforts, including beekeeping. The Agricultural Research and Extension Trust (ARET) manages the catchment. The reservoir, commissioned in 2017, had no prior sedimentation assessment; therefore, this study is the first to provide bathymetric data and sedimentation analysis.



(**a**) Catchment area of Mwimba Reservoir in Kasungu, Malawi

(**b**) Soil map for Mwimba Reservoir catchment area

(**c**) Land Use Cover map for Mwimba Reservoir catchment area

Figure 1. Mwimba Reservoir catchment area in Kasungu, Malawi.

Geologically, the Mwimba catchment lies within the Basement Complex formation, which is predominantly composed of granitic and gneissic rocks. The overlying soils are generally ferrallitic, sandy loams, and moderately acidic, with high erodibility under intensive land use, as shown in **Figure 1b** [21]. These lithological and soil characteristics contribute to the reservoir's vulnerability to sediment influx, especially in areas with minimal vegetation cover or active cultivation. The gentle to moderately sloping topography further facilitates surface runoff, enhancing soil detachment and transport during rainfall events.

Land use within the Mwimba Reservoir catchment comprises predominantly cropped land, tall trees, range land, and built-up areas, as depicted in **Figure 1c** [21]. Cropped land constitutes the most significant proportion of the catchment, covering nearly 60% of the area, and is associated with rainfed cultivation of maize, tobacco, and legumes. Rangeland and areas under natural vegetation (tall trees) cover about 30% of the basin, providing partial soil protection, especially in upland zones. Built-up areas and infrastructure contribute around 8%, while water surfaces account for less than 2%. This distribution indicates a moderate to high potential for sediment generation, particularly from cultivated slopes adjacent to stream inflows. The dominance of agriculture emphasises the need for integrated catchment management practices—such as contour tillage, buffer strips, and vegetative cover—to mitigate soil erosion and reduce sediment delivery into reservoirs.

2.2. Bathymetric Survey

A bathymetric survey was conducted to measure the depth and volume of the reservoir. The bathymetric survey method is widely regarded as the most direct and accurate approach for assessing sedimentation in reservoirs, particularly in small to medium-sized water bodies [19]. By comparing the original reservoir capacity (obtained from the 2017 design specifications) with the current capacity in 2022, this study aimed to quantify sediment accumulation over five years. The original design volume of 89,200 m³ was sourced from the Mwimba Reservoir engineering design documents and technical drawings [22] submitted to the Agricultural Research and Extension Trust (ARET) during commissioning in 2017. These documents served as the baseline reference for comparative analysis.

The bathymetric survey was performed on March 19, 2022, when the reservoir was at Full Supply Level (FSL). A grid-based survey design was employed, ensuring adequate spatial coverage of the reservoir. A total of 507 survey points were established along 23 transects spaced 15 meters apart (**Figure 2**). This design ensured comprehensive coverage and accurate representation of sediment deposition across the reservoir bed. Such grid-based surveys have been shown to provide precise estimates of reservoir capacity by capturing variations in depth across the entire surface [6,19].

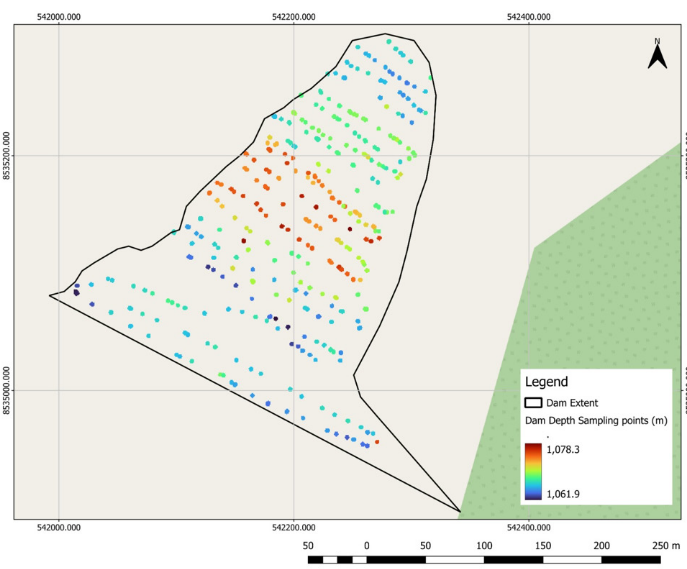


Figure 2. Bathymetric survey points.

Depth measurements were collected using a 5-meter staff gauge equipped with a flat plate to measure vertical distances. The staff was lowered to the reservoir bed, and depth readings were recorded at each survey point. A handheld GPS device was used to record the exact coordinates of each measurement point, ensuring spatial accuracy. The combination of a staff gauge and GPS provides a cost-effective and reliable means of collecting bathymetric data, particularly in resource-constrained environments [20].

2.3. Data Analysis Using GIS

The collected depth data were imported into ArcGIS 10.3 for analysis. The GPS coordinates and depth measurements were used to develop a Triangulated Irregular Network (TIN) surface model of water depth in the reservoir. The TIN model is a vector-based digital representation of terrain that utilises irregularly spaced points connected by non-overlapping triangles to model surface morphology [23,24]. This method is particularly effective in capturing detailed bathymetric features because it preserves break lines and accommodates sharp changes in slope, which are common in reservoir beds influenced by sedimentation [25,26].

Compared to raster-based methods, TIN models offer greater accuracy when the dataset contains variable point spacing or when the surveyed area has complex topography [27–29]. In the context of sedimentation studies, TIN enables precise volumetric calculations [30] and spatial visualisation of sediment distribution [31] by interpolating between measured depth points. The TIN model enabled the calculation of the reservoir's current volume using the 3D Analyst Area and Volume tools in ArcGIS. The difference between the designed volume in 2017 and the measured volume in 2022 provided an estimate of the sediment accumulation. To test the significance of the observed volume change, a one-sample T-test was applied comparing the 2022 surveyed volume to the designed initially volume of 89,200 m³. This test was conducted at a 95% confidence level to determine whether the reduction in reservoir capacity was statistically significant. The TIN surface model created from bathymetric data was used to map sediment distribution patterns, identifying areas with the highest levels of deposition.

2.4. Sediment Load Estimation

To quantify the sediment load in the reservoir, water samples were collected from seven random locations within the reservoir. These samples were analysed in the laboratory to determine sediment concentration using the filtration method. The filtration method for measuring Total Suspended Solids (TSS) is a standard approach in sediment studies, providing an accurate assessment of sediment concentration in water samples [32]. Sediment bulky density was determined, allowing for conversion of the sediment volume to mass using Equation (1):

$$TSS_{load} = SV \times \rho_b \tag{1}$$

where *TSS* load is the total suspended sediment load (kg or tonnes), *SV* is the sediment volume, and ρ_b is the sediment concentration or bulk density (kg/m³) as provided in Equation (2):

$$\rho_b = \left[\frac{W_{sand} + W_{clay+silt}}{V_{sample}}\right] \times 10^6 \tag{2}$$

where W_{asnd} is weight of sand, $W_{clay\ +\ silt}$ is of suspended clay and silts and V_{sample} the volume of the sample.

The sedimentation rate (*SR*) in tonnes/year was calculated as a linear relationship between sediment yield and the accumulation period, using Equation (3):

$$SR = \frac{SV \times \rho_b}{Y} \tag{3}$$

where *Y* represents the number of years since the reservoir's commissioning in 2017. Estimating sedimentation rates based on the time since commissioning is a widely accepted method for understanding how sediment accumulates over time and predicting future capacity loss [6].

2.5. Reservoir Life Estimation

The remaining useful life of the Mwimba Reservoir was estimated using the approach by Yusuf and Yusuf [33], which relates reservoir volume to sedimentation rate [Equation (4)]:

$$T = \frac{total\ volume\ of\ the\ reservior}{sedimentation\ rate} * 50\% \tag{4}$$

The useful life of a reservoir is defined as the time it takes to exhaust 50% of its loading capacity or fill the dead storage with silt [14,34].

3. Results

The results of this study provide critical insights into the current sedimentation status of Mwimba Reservoir, including changes in reservoir capacity, sediment accumulation rates, and the spatial distribution of sediment within the reservoir. Each component of the analysis contributes to a comprehensive understanding of how sedimentation has affected the reservoir over the five years period from 2017 to 2022.

3.1. Reservoir Capacity and Volume Loss

The bathymetric survey data in **Figure 3** reveal significant sediment accumulation in Mwimba Reservoir, resulting in a substantial reduction in its storage capacity. The original design volume of the reservoir in 2017 was 89,200 m^3, while the current volume, as calculated from the bathymetric data, was 72,966 m^3, indicating a loss of 16,234 m^3 of storage capacity. This represents an 18.2% reduction over the five years period.

Statistical analysis using a one-sample T-test, comparing the 2022 volume against the original design volume, confirmed that the reduction is statistically significant ($p = 0.013$, $\alpha = 0.05$). The annual rate of capacity loss was calculated as 3.64% per year. This rate is consistent with sedimentation in similar small reservoirs located in agricultural catchments, where upstream land use changes accelerate sediment transport.

The reduction in volume is primarily attributed to sediment deposition near the reservoir's main inflow points.

3.2. Sedimentation Rate and Sediment Load

The total suspended sediment (TSS) load, derived from water samples collected at seven points across the reservoir, indicated an average sediment concentration of 338 mg/L. The bulk density of the sediments, measured in the laboratory, was 0.000386 tonnes/m^3. Using the sediment volume and bulk density data, the total sediment load was calculated to be 6.27 tonnes. The sedimentation rate, based on the five years period since commissioning, was estimated at 1.25 tonnes per year.

This relatively low sedimentation rate, compared to other small reservoirs in Malawi and neighbouring countries, may be attributed to adequate vegetation cover and conservation practices in parts of the catchment. Nevertheless, the cumulative loss of storage capacity is significant, warranting continuous monitoring and proactive measures to control sediment.

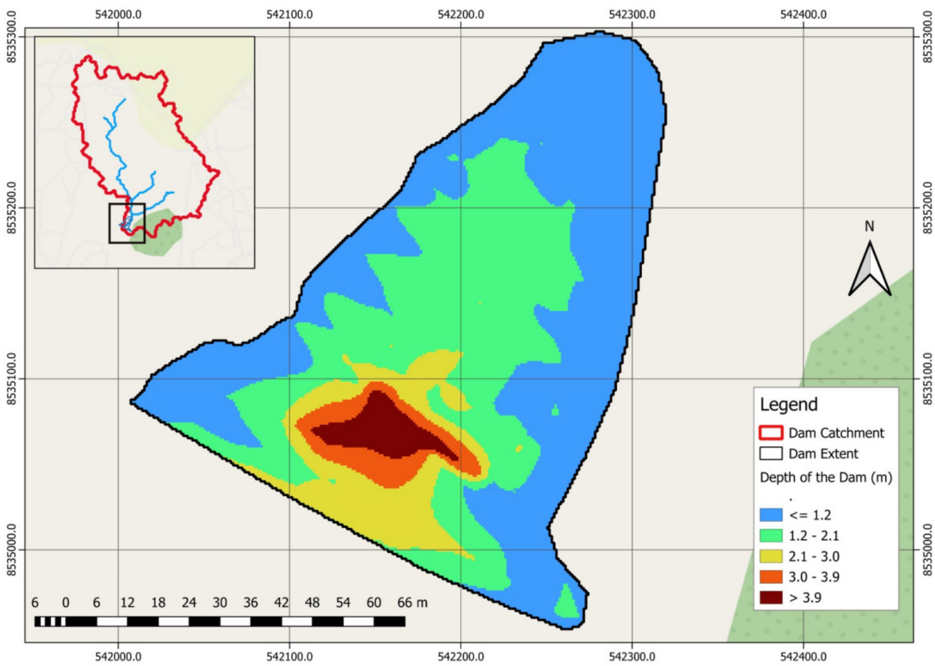


Figure 3. Bathymetric data forming Triangulated Irregular Network (TIN) surface model of water depth in Mwimba reservoir as of 2022.

3.3. Spatial Distribution of Sedimentation

The GIS-based analysis of the sediment distribution within Mwimba Reservoir revealed distinct patterns of sediment deposition. Areas near the primary inflow points exhibited higher levels of sediment accumulation, as evidenced by the low water depth recorded in these areas, particularly in the northeastern part of the reservoir, where inflows from seasonal streams are concentrated. The spatial distribution map (**Figure 2**) shows that sediment accumulation is more pronounced in these areas, with water depths reduced to as low as 0.15 meters.

The maximum water depth of the reservoir, recorded near the dam wall, was 4.92 meters, indicating that sediment accumulation in this region is significantly lower. On average, the depth of the reservoir was reduced to 1.37 meters across the surveyed points, compared to the initial average design depth of 2 meters at the Full Supply Level (FSL). These results highlight the uneven nature of sediment deposition, with areas closer to inflow points being more vulnerable to rapid sediment accumulation.

3.4. Estimated Reservoir Life

Based on the calculated sedimentation rate of 1.25 tonnes per year and the current capacity loss of 16,234 m^3, the remaining operational life of Mwimba Reservoir was estimated using the reservoir life projection model. The model suggests that, without intervention, the reservoir could lose up to 50% of its live storage capacity within the next 27.5 years from its commissioning in 2017. This projection highlights the necessity for targeted sediment management strategies, particularly upstream erosion control measures, to mitigate sediment inflow from agricultural activities.

3.5. Comparison with Regional and Global Sedimentation Trends

The sedimentation rate (1.25 tonnes per year) observed in Mwimba Reservoir, although lower than that of other small reservoirs in the region, still poses a significant long-term threat to the reservoir's functionality. Similar studies, such as those by Bihonegn and Awoke[10], have reported sedimentation rates as high as 2.7 tonnes per year in Ethiopian reservoirs like Koka and Shumburit, highlighting the variability in sedimentation rates based on catchment characteristics. The observed annual capacity loss of 3.64% in Mwimba Reservoir falls within the typical range for reservoirs globally, where sedimentation rates vary between 1% and 5% annually, depending on land use practices and catchment management. Studies by Wisser et al. [9] revealed an annual average loss capacity of 3.4% across Africa.

4. Discussion

The findings of this study provide important insights into the sedimentation processes and their impacts on Mwimba Reservoir over the five years period from 2017 to 2022. The results not only quantify the extent of sediment accumulation but also highlight the need for targeted sediment management strategies to extend the operational lifespan of the reservoir. In this section, the key results are interpreted in the context of existing literature, and implications for reservoir management are discussed.

4.1. Reservoir Capacity Loss

The study revealed that Mwimba Reservoir has experienced an 18.2% reduction in storage capacity since its commissioning in 2017, with an annual capacity loss rate of 3.64%. This reduction is significant and suggests that sedimentation is already having a noticeable impact on the reservoir's ability to store water for agricultural and domestic use. The observed capacity loss is comparable to that of other small reservoirs in Africa, where sedimentation rates typically range from 2% to 5% per year [10,35].

The higher-than-expected sedimentation in Mwimba Reservoir, despite its relatively low sedimentation rate in tonnes, can be attributed to several factors, including land-use changes in the catchment area, particularly agricultural expansion and deforestation. These activities increase soil erosion and the transport of sediments into the reservoir, which is consistent with findings from similar studies in Ethiopia [6,14].

4.2. Sedimentation Rate and Load

The sedimentation rate of 1.25 tonnes per year observed in Mwimba Reservoir is lower than rates reported in similar studies within Africa. For example, the Koka Reservoir in Ethiopia reported 2.7 tonnes per year due to extensive upstream land degradation [10], while the Shumburit Reservoir experienced 60,390 tonnes annually [14]. These differences highlight the significance of localised environmental and anthropogenic factors.

In the Mwimba catchment, several factors may explain the comparatively low sedimentation rate. The presence of natural woodland cover and beekeeping conservation zones upstream has contributed to reduced erosion and sediment transport. Furthermore, ARET's controlled land use and community outreach on soil conservation may have had a mitigating effect on sediment yield. The relatively stable hydrology of the seasonal streams feeding into the reservoir, with moderate flow velocities, may also reduce sediment-carrying capacity during the rainy season.

Despite the lower sedimentation rate, the annual volume loss of 3.64% is a clear indicator that without intervention, the reservoir's operational life will continue to decline. The estimated remaining life of 27.5 years aligns with global trends for small reservoirs experiencing moderate but cumulative sedimentation impacts [4,6].

4.3. Spatial Patterns of Sediment Deposition

The GIS-based analysis of sediment distribution revealed that the majority of sediment deposition occurred near the main inflow points, particularly in the northeastern part of the reservoir. This pattern is typical of reservoirs where inflows carry sediment loads that settle as the water velocity decreases upon entering the reservoir [20]. Similar findings have been reported in Ethiopian reservoirs, where sedimentation hotspots were identified near inflow points, necessitating targeted sediment trapping measures [14].

The uneven nature of sediment deposition, with depths reduced to as low as 0.15 meters in certain areas, underscores the importance of spatially explicit sediment management. By identifying sediment hotspots, targeted interventions such as sediment traps, check dams or periodic dredging can be implemented to reduce sediment load and prevent further volume loss.

4.4. Management Implications for ARET and Local Communities

The findings carry direct implications for the Agricultural Research and Extension Trust (ARET), which manages the reservoir and its catchment. First, the projected 27.5-year operational life signals a clear need for early action. ARET can integrate sediment control into its agricultural extension programs, promoting practices such as conservation tillage, contour farming, and vegetative buffer strips.

Second, since the reservoir supports irrigated agriculture and domestic use for surrounding communities, sedimentation poses a socio-economic risk. Capacity loss reduces water availability during dry periods, directly affecting crop yields and livelihoods. Community-based sediment monitoring and education, through village natural resource management committees, would enhance local ownership of sediment control initiatives.

4.5. Comparative Insights and Future Interventions

The sedimentation rate and capacity loss observed in Mwimba Reservoir fall within the typical range for small reservoirs in Sub-Saharan Africa. However, early intervention will be critical to prevent accelerated degradation. Strategies such as upstream afforestation, gully reclamation, and buffer zone protection, which have proven effective elsewhere [18], should be prioritised. Check dams and sediment basins at the mouths of inflowing streams could intercept sediments before they settle within the reservoir body.

4.6. Limitations and Recommendations for Future Research

While this study provides valuable baseline data on sedimentation in Mwimba Reservoir, several limitations should be acknowledged. The analysis assumes a constant rate of sedimentation, which may vary annually due to changes in rainfall patterns and land use. Seasonal sampling and longer-term monitoring provide a more nuanced understanding.

Future research should integrate hydrological and erosion modelling (e.g., SWAT or RUSLE models) with socio-economic assessments of land-use practices to link erosion risk with human activity. Remote sensing techniques such as NDVI or land-cover change detection could offer deeper insights into the drivers of sediment yield.

5. Conclusion

This study has established a baseline sedimentation status for Mwimba Reservoir in Kasungu, Malawi, using bathymetric surveys and GIS analysis. The findings demonstrate that sedimentation is a critical issue impacting the reservoir's storage capacity, with an observed 18.2% reduction in capacity over five years, resulting in an annual capacity loss rate of 3.64%. The current sedimentation rate of 1.25 tonnes per year poses a significant long-term threat to the reservoir's operational life, which is projected to decrease by 50% within the next 27.5 years without intervention.

The spatial distribution of sediment deposition reveals that the majority of sediment accumulation occurs near the inflow points, particularly in the northeastern section of the reservoir, where sediment deposition has reduced depths to 0.15 meters in some areas. These sediment hotspots highlight the need for targeted management interventions, such as the installation of sediment traps and check dams, to mitigate further capacity loss.

A comparative analysis with regional and global sedimentation trends confirms that the sedimentation rate of Mwimba Reservoir is relatively low compared to other reservoirs in the region. However, the cumulative impact of sedimentation, compounded by upstream land use changes such as deforestation and agricultural expansion, necessitates proactive management to prevent further degradation of the reservoir's functionality. Implementing Best Management Practices (BMPs), including reforestation, terracing, and the establishment of vegetation buffers, is crucial for reducing sediment inflow from the catchment. Additionally, integrating sediment-trapping structures could significantly prolong the operational lifespan of the reservoir. Continuous monitoring of sedimentation rates, combined with catchment-level interventions, will be critical to sustaining Mwimba Reservoir as a vital water resource for the surrounding communities.

While this study provides a valuable baseline for the sedimentation status of Mwimba reservoir, further research is needed to fully understand the sources of sediment within the catchment. A comprehensive catchment analysis, including soil erosion modelling and land-use mapping, could provide deeper insights into the key drivers of sedimentation and inform targeted mitigation strategies. Additionally, long-term monitoring of sedimentation trends using advanced remote sensing techniques could enhance the accuracy of future assessments and support adaptive management practices.

Author Contributions

R.M.S and P.G.K.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, writing original draft, writing review and editing. L.F and G.C.: Conceptualization, Investigation, Methodology, Supervision, writing review and editing. L.K.: Validation, writing review and editing. All authors have read and agreed to the published version of the manuscript.

Funding

The authors would like to thank the Agricultural Research and Extension Trust of Malawi and the Centre of Excellence of Transformative Agriculture Commercialisation at Lilongwe University of Agriculture and Natural Resources for supporting this study.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data is available from the author upon request.

Acknowledgments

The authors are greatly indebted to the Agricultural Research and Extension Trust of Malawi for the assistance rendered during the study. The manuscript originated from

Raphael Mathews Steven's research work for a Master of Science Degree in Irrigation Engineering, undertaken while he was a student at Lilongwe University of Agriculture and Natural Resources in 2022.

Conflicts of Interest

All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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