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Navigating the Depths: An Assessment of the Management and Operations of Alau Dam Reservoir

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Abstract: **The management and operation of water reservoirs particularly in regions susceptible to climate change and inadequate resource utilization requires careful consideration. This research focuses on the Alau dam situated in Northern Nigeria, a critical water source for the region. Despite its significance, the dam's performance faces challenges such as sedimentation, flooding, and insufficient adaptation to climate change. This study investigates the current state of management and operations at the Alau dam's reservoir emphasizing the frequency, challenges, and existing strategies. Utilizing a mixed-methods approach, including interviews, field observations, and analysis of water quality and water level, and aerial imagery. The study investigates the impact of these factors on the dam's capacity, functionality, and structural integrity. Over time, sediment deposition has substantially reduced the reservoir's effective storage capacity, leading to a misleading increase in surface area without corresponding water volume, thereby heightening the risk of overtopping and structural failure. Additionally, delayed and inflexible water release practices have exacerbated downstream flooding, while placing excessive hydraulic pressure on the dam's infrastructure, particularly the earthen embankments. The absence of a sediment management plan, coupled with inadequate maintenance, has further compromised the dam's operational effectiveness and increased the likelihood of catastrophic failure. This study highlights the need for a shift toward adaptive management practices, including sediment removal, regular maintenance, real-time monitoring, and the incorporation of environmental flows. Recommendations include the implementation of a data-driven water release policy, infrastructure upgrades, secondary storage systems, and enhanced stakeholder engagement. These measures are critical for reducing flood risks, preserving downstream ecosystems, and ensuring the long-term sustainability and safety of the Alau Dam.**

***Keywords*: Alau dam, reservoir management and operations, sustainable management, climate change, environmental concerns.**

1. INTRODUCTION

The management and operation of dams and reservoirs are critical for ensuring their safety, health and productivity over their intended lifespan. The Alau dam located in a geographic region that depends on effective management of water resources by storage reservoirs provides water for basic needs and stores surplus water during high flow seasons to provide protection of downstream areas from flooding. The performance of dams in Nigeria falls short of expectations as poor maintenance is often observed (Adeogun et al., 2018). This can be attributed to the underutilization of water resources and management issues (Babagana et al., 2015). Most schemes rely on historical data to operate while the design and operation of reservoir systems based on historical data may not account for the impact of climate change (Fluixá-Sanmartín et al., 2018). Therefore, scientific research is being conducted to identify the risks associated with current reservoir operation practices in the face of climate change-induced challenges such as altered precipitation patterns and extreme weather events (Ehsani et al., 2017). Climate change is expected to cause alterations in streamflow patterns leading to changes in the operation of water structures, emphasizing the importance of assessing the potential impact of climate change on the management and operation of dams (Fluixá-Sanmartín et al., 2018). This assessment is crucial for enhancing preparedness for water availability, disaster management, and dam safety; thus, it is crucial to investigate the current understanding of dam reservoir management and operation concerning challenges such as flooding, sedimentation, and changes in flow frequency with a focus on the potential impacts of climate change (Guyennon et al., 2017). For water supply systems, sediment build-up in dam reservoirs is unsustainable since it may result in decreased storage capacity which would impact water delivery and raise maintenance costs (Lee et al., 2022). While all reservoirs naturally experience sedimentation, climate change has the potential to exacerbate the issue by intensifying weather patterns (IPCC, 2021). This can lead to an increase in sediment loads which can negatively affect the functioning of these structures (Laura et al., 2017). To maintain the long-term sustainability of water supply systems, adaptive management techniques should be taken into account to lessen the effects of sedimentation (Wang et al., 2018). To effectively limit the effects of sedimentation, it is critical to evaluate the management and operation of dams (Obialor et al., 2019). The timing of major flood inputs and reservoir operations have a significant impact on the distribution patterns of sediment deposit (Juško et al., 2022). To guarantee the long-term viability of reservoirs, it is crucial to create sustainable sediment management methods and assess present management techniques (Daramola et al., 2019). It has been determined that community flooding downstream is caused by Alau dam reservoir management and operation. This pose risks to local communities' safety and livelihoods and forces biodiversity adaptation and migration. Furthermore, holding back water for longer periods during dry periods leaves downstream areas dry for most of the year impacting the environment and local communities negatively. Thus, there is an urgent need to evaluate current management and operational practices at the Alau dam's reservoir and identify ways to improve them to reduce the risk of flooding and minimize negative environmental and societal impacts. This study evaluated the effectiveness of the current management and operational practices of the reservoir making sure of the sustainable use of the river's resources and lowering the risk of flooding downstream by incorporating the frequency and timing of water releases from the reservoir as well as the problems and challenges associated with the reservoir management in the assessment.

2. DATA AND METHODS

2.1 Study location

Alau dam is located in north-eastern Nigeria, 19 km south-east of Maiduguri. Maiduguri and Jere have an annual rainfall below 600mm with the raining season starting in July through October, followed by a period of harmattan occurring between November and February. The region located in an arid zone experiences a very hot dry season from March through July (Wakil et al., 2014). The Alau dam was constructed in 1985 following the need to reduce downstream flooding from river Ngadda upstream located at latitudes 11°N and 12°N and longitudes 13°E and 14°E (figure 1). Soon the dam has secondary functions including water supply and irrigation. The reservoir created as a result of damming river Ngadda open avenues for people to earn a living from as it serves as a major source of fishing activities for Jere and environs (Wakil et al., 2016).

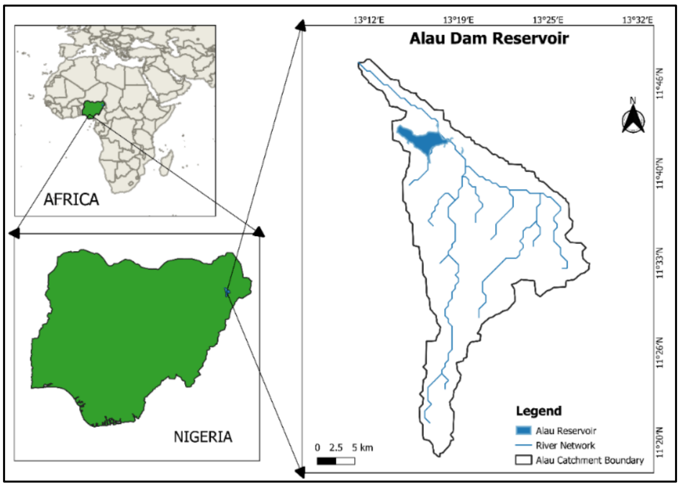

Figure 1: Location map of the study site

2.2 Data collection

Data collection for this study utilized a mixed-methods approach to ensure a thorough understanding of the challenges and solutions in the management and operations of the Alau dam reservoir. The methods included face-to-face interviews, virtual interviews via phone, comprehensive field visits, and the incorporation of various secondary data sources. The structured interview guide covering key aspects of the research subject including the management and operation of Alau dam and reservoir, control and regulation, ecological consideration, and environmental flow consideration and policies was administered to the Chad Basin Development Authority (CBDA) staff. During field visits, the research team observed the physical conditions of the study site, collecting additional data related to the research problem. Simultaneously, available water quality data from the Maiduguri water treatment plant (January 2020 – November 2022) was collected to enrich the understanding of ecological considerations. Aerial images from Landsat 8 were retrieved (September 2022) when the reservoir is at its peak level to identify the Dam site and reservoir wet surface area. Various measurements including surface area and perimeter were extracted from the images. To ensure accuracy, a scale factor was assigned by measuring the dam's auxiliary spillway which is a known dimension. Furthermore, time-series data on reservoir water levels from 1990 to 2022 was obtained from the CBDA in Maiduguri, Borno state. This extensive dataset provides historical context and facilitates the examination of trends over a more extended period.

2.3 Data analysis

2.3.1 Interview and field observation

Responses from face-to-face and virtual interviews was subjected to content analysis. The designed themes were based on operation, management, infrastructure, maintenance and dam design. Observational data gathered during field visits were qualitatively analysed to provide contextual insights into the physical conditions of the study site and supplement the interview findings and other data collected.

2.3.2 Water quality

The water quality data obtained from the Maiduguri water treatment plant (January 2020 to November 2022) was presented on graphs. Relationships between parameters such as pH and temperature, and turbidity and colour were displayed to understand the ecological considerations related to the reservoir.

2.3.3 Aerial imagery

Aerial images from Landsat 8 were analysed using remote sensing techniques. Surface area and perimeter measurements extracted from the images contributed to understanding of the spatial characteristics of the dam and reservoir site. An assigned scale factor derived from the dam's auxiliary spillway was applied to ensure accuracy in the aerial imagery analysis. The aerial imagery was analysed using QGIS to estimate the reservoir capacity from the Digital Elevation Model (DEM), the SRTM 30-meter DEM was utilized. After obtaining the elevation of the reservoir, a geographical coordinate was set to an equal area projection to visually represent the reservoir similar to standard maps. Contour lines were created at 2-meter intervals using Raster Extraction, and the lines were filtered based on the reservoir's elevation. Advanced digitizing tools were employed to edit and clean the contour lines, resulting in a validated polygon. The DEM underneath the reservoir was then extracted, and the elevation-area-volume relationship was calculated by selecting the DEM layer and utilizing the Raster Surface Volume tool. This process, repeated for various elevation intervals, provided a detailed understanding of the reservoir's capacity. The reservoir volume was calculated as follows:

Reservoir volume = $0.0086 \times \text{Surface area}^{1.44}$ (Sawunyama et al., 2006) (1)

Reservoir volume = $0.00857 \times \text{Surface area}^{1.4367}$ (Liebe et al., 2005) (2)

These two established formulas were then employed to approximate the reservoir capacity. The formulas has been used in Limpopo river basin to measure the capacity, the results showed that the use of remotely sensed surface area-volume relationship is indeed feasible (Sawunyama et al., 2006; Liebe et al., 2005). This methodology ensures accuracy through systematic analysis and validation of the digital elevation model.

2.3.4 Reservoir water level

The time-series data on reservoir water levels from 1990 to 2022 undergo temporal analysis to identify patterns, trends, and potential correlations with management practices and environmental factors. The data was plotted on a graph and the time-series analysis and trend detection was obtained graphically to assess the variability and long-term dynamics of the reservoir water levels.

2.4 Ethical Considerations

This investigation was conducted with ethical considerations in mind. All subjects gave their informed consent and the study maintained their anonymity and confidentiality. The University of Maiduguri Research Ethics Committee created pertinent standards and regulations regarding research ethics which were adhered to during the studies.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Dam Design, Management and Operation

The Alau dam reservoir has a designed capacity of 112 million cubic meters when the dam commenced operations in 1986. A capacity that has been questioned due to sediment deposition into the system. This reported capacity may no longer accurately represent the current state of the reservoir. The Dam can be said to be under capacitated in this regard. The water treatment plant pumps out 4.5 million litres per day, abstracting a total of 11.4 billion litres yearly from the reservoir, which is 10% of its designed capacity. Though large amounts of water flow downstream to Jere Bowl for irrigation, this amount is not accounted for. Table 1 presents the hydraulic design and physical properties of the Dam obtained from the Chad Basin Development Authority (CBDA).

Table 1: Alau dam hydraulic design

Components		Value/Type/Purpose	
1	Length [m]	60	
2	Height [m]	9	
3	Type of Dam	Masonry/Earth	
4	Dead Storage [m]	2.25	
		Width [m]	**Height [m]**
5	Spillway Crest	60	9.0
6	Sluice gate	4.5	2.5
7	Intake from Reservoir	Water Supply	
8	Intake Position	Bottom	
9	Intake Pipe Diameter	0.8 m	

During the field visit to the dam site, poor management and maintenance issues with the infrastructure were identified. The spillway is partially collapsed exhibiting extensive damage to structural members (figure 2a) and the dam crest is on the verge of complete collapse likely to be attributed to both the force of water flow and structural failures induced by erosion on some part of the dam foundation (figure 2b).

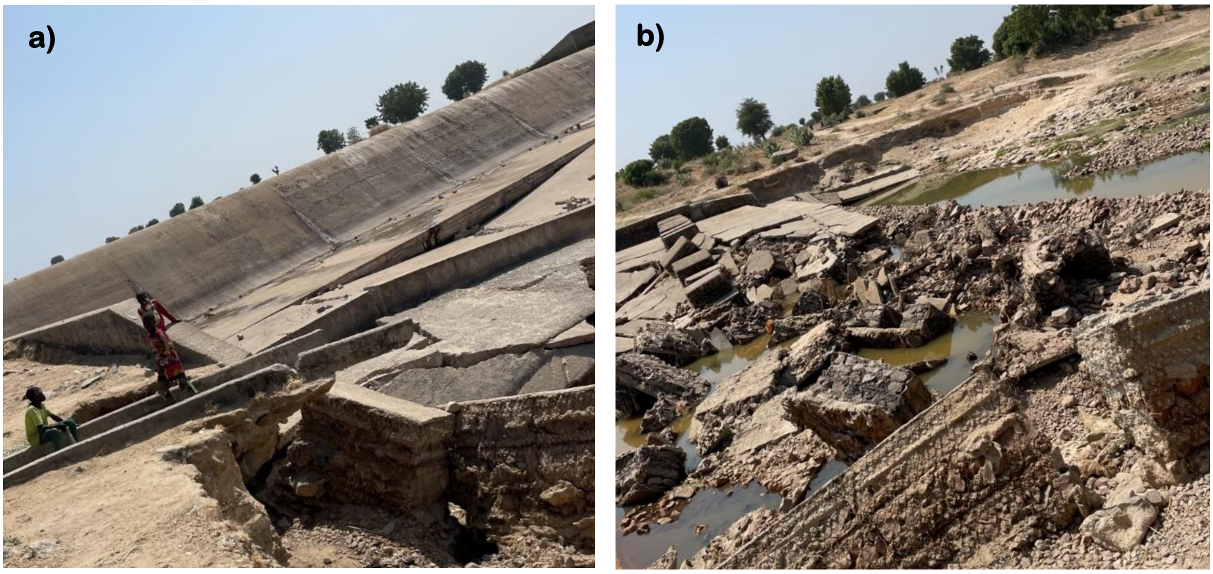

Figure 2: a) Partially collapsed dam spillway, b). Collapsed dam crest.

3.1.2 Sedimentation and Reservoir Capacity

The Alau Dam reservoir's current surface coverage, as depicted in Figure 3, reveals significant deviations from its original design parameters. When the dam commenced operations in 1986 under the supervision of the Chad Basin Development Authority (CBDA), the designed capacity was reported as 112 million cubic meters (MCM). However, satellite imagery from September 2022 suggests that the reservoir is now handling substantially more water than originally intended. Using empirical surface area-volume relationships, two calculated volumes of 296 MCM and 279 MCM were derived, representing a 6% discrepancy attributable to variations in coefficients used in the calculations (Table 2). Despite this discrepancy, it is clear that the reservoir's capacity has changed dramatically over time. Sedimentation within the reservoir may have significantly reduced its effective storage capacity, leading to increased stress on the dam structure during high inflow periods. This sedimentation, coupled with insufficient infrastructure upgrades and maintenance, may have resulted in the dam being under capacitated and unable to manage the increased hydrological load.

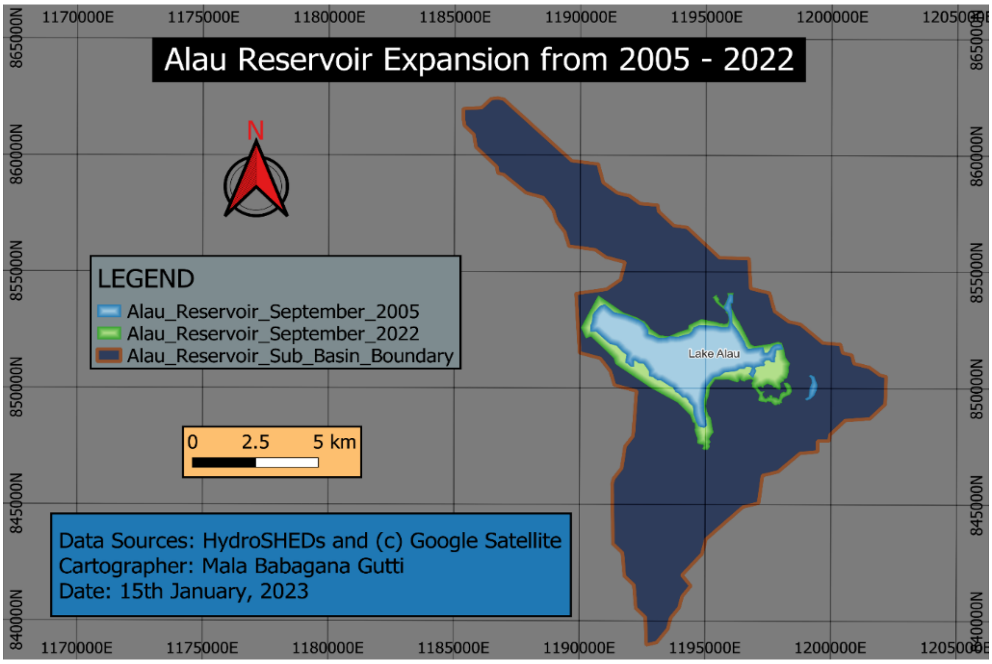

Figure 3a: Satellite imagery GIS extract showing Alau reservoir expansion.

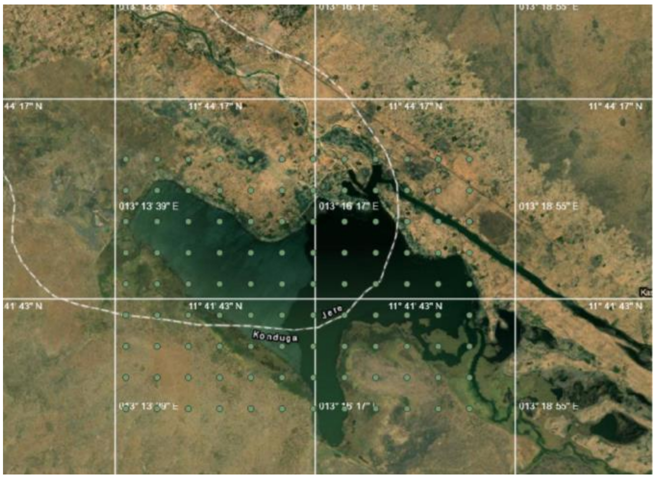

Figure 3b: Satellite imagery showing Alau reservoir.

Table 2: Results of reservoir surface area-volume relationship

Surface Area			
S/N	**Items**		**Value**
1.	Wet Surface Area (m^2)		20,760,000
2.	Linear Precision (cm)		± 2
Calculated Reservoir Capacity			
S/N	**Items**	**Area-Volume Relationship**	**Value**
1.	Volume (m^3)	$V = 0.0086 \times Area^{1.44}$ (Sawunyama et al., 2006)	296,009,626
2.	Volume (m^3)	$V = 0.00857 \times Area^{1.4367}$ (Liebe et al., 2005)	279,023,868

3.1.3 Hydrological Management and Water Release Practices

Operational practices at the Alau Dam contribute significantly to its inability to manage water levels effectively. The scheme follows a management approach where the spillway sluice gates are opened only once annually, typically when the water level reaches 329 meters above mean sea level (MSL) in August or September and remain open for a prolonged three-month period. This operational strategy does not provide the necessary flexibility to manage the reservoir's water levels throughout the year effectively. Inconsistent release schedules have led to both overflows and flood events downstream, particularly impacting the communities along the Ngadda River. The analysis of operational records and historical water level data (Figure 4) indicates that the water level fluctuates between 329m and 330m throughout the spilling months, indicating poor planning and delayed water releases as these levels are already above the free zone of the dam. This lack of an effective forecasting and planning further compounds the issue, leaving the dam vulnerable to unexpected overtopping and flooding during peak inflow periods.

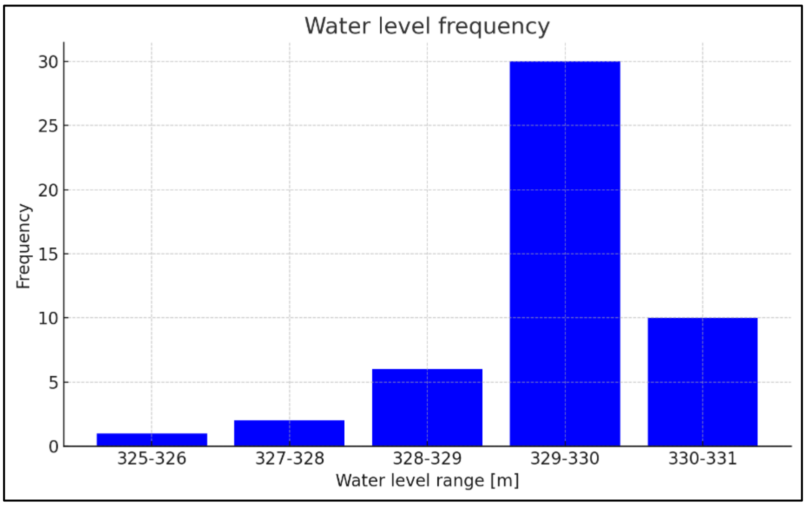

Figure 4: Frequency of flow release from Dam.

3.1.4 Water Level Trends and Historical Operations

From long-term water level data (Figure 5), it is evident that the Alau Dam reservoir consistently reaches peak water levels in August and September, likely due to a combination of reduced demand for water during these months and the reservoir's seasonal recharge. The historical analysis also shows that the peak water levels over the last 30 years have consistently been in September, a trend that should have allowed dam operators to predict and manage water releases more effectively. However, poor operational planning has resulted in frequent flooding. The data indicates that floods continue to affect downstream communities, despite decades of operational records that could have informed better management practices. This reinforces the notion that inadequate planning, rather than lack of information, is responsible for the dam's hydraulic failures over the years.

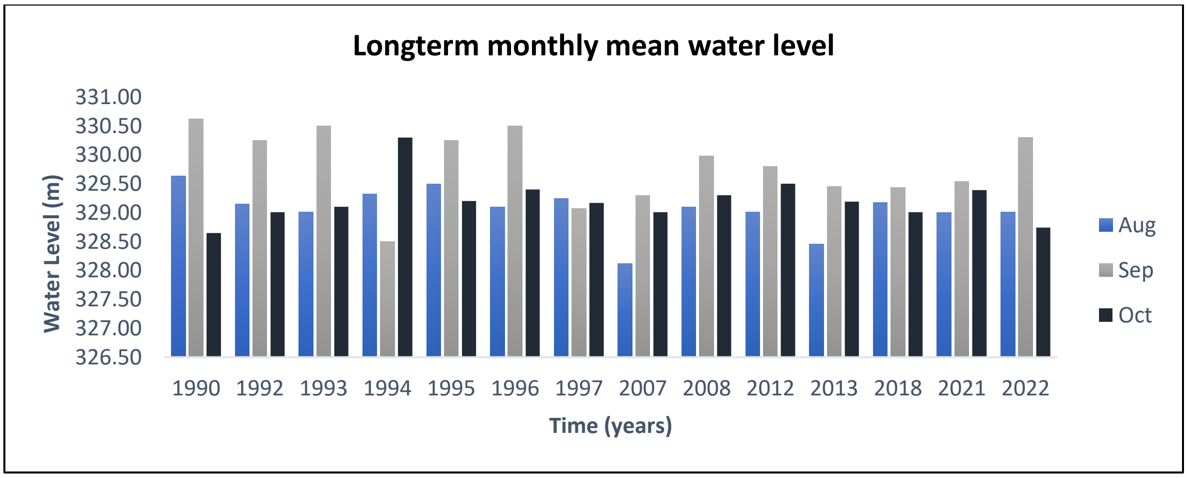

Figure 5: Peak months of water level of Alau reservoir

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3.1.5 Water Quality and Environmental Concerns

The quality of water within the Alau Dam reservoir was found to be moderately acceptable, with pH levels generally ranging between 7.0 and 8.0, indicating neutral to slightly alkaline conditions. However, there were occasional deviations with low pH values between 0.5 and 4.0 (Figure 6), which point to potential pollution events, possibly linked to agricultural runoff and other economic activities upstream. Turbidity levels (Figure 7) and colour concentrations indicated moderate pollution, primarily from suspended matter and other contaminants introduced through upstream agricultural activities, including waste from small-scale farms and brick moulding enterprises (Figures 8a and 8b). Additionally, unsustainable fishing practices were noted during field visits, despite existing policies aimed at conservation (Figures 8c and 8d). Enforcement of these policies was found to be weak, with little effort to ensure sustainable land use and fishing practices around the reservoir. Moreover, the dam's operational model does not consider environmental flows, leading to significant downstream ecological degradation as discharge from the dam is solely regulated by water level management and flood control needs.

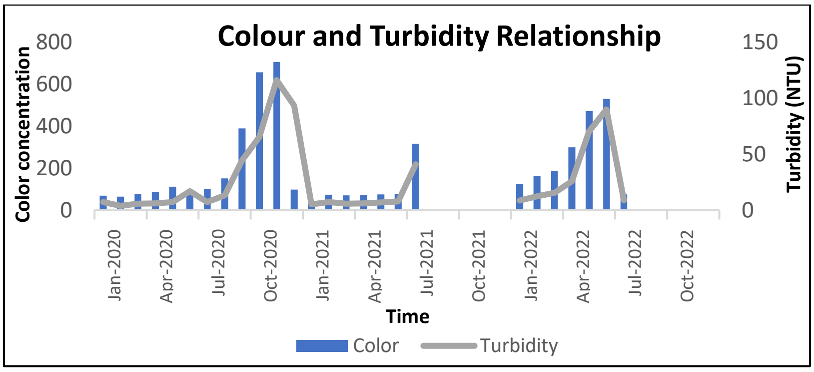


Figure 6: Colour and Turbidity in Reservoir

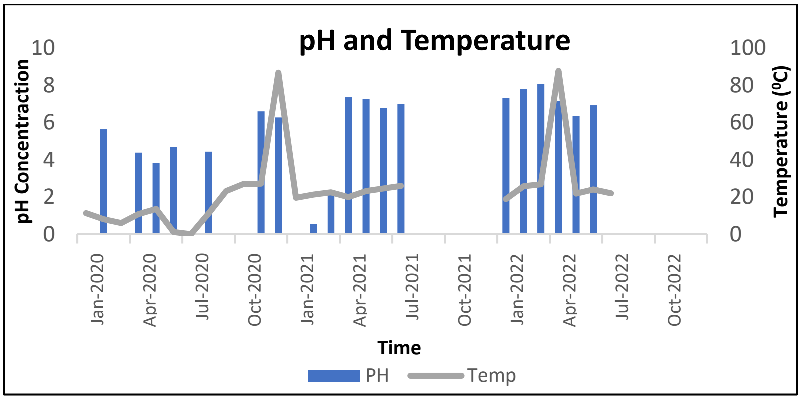
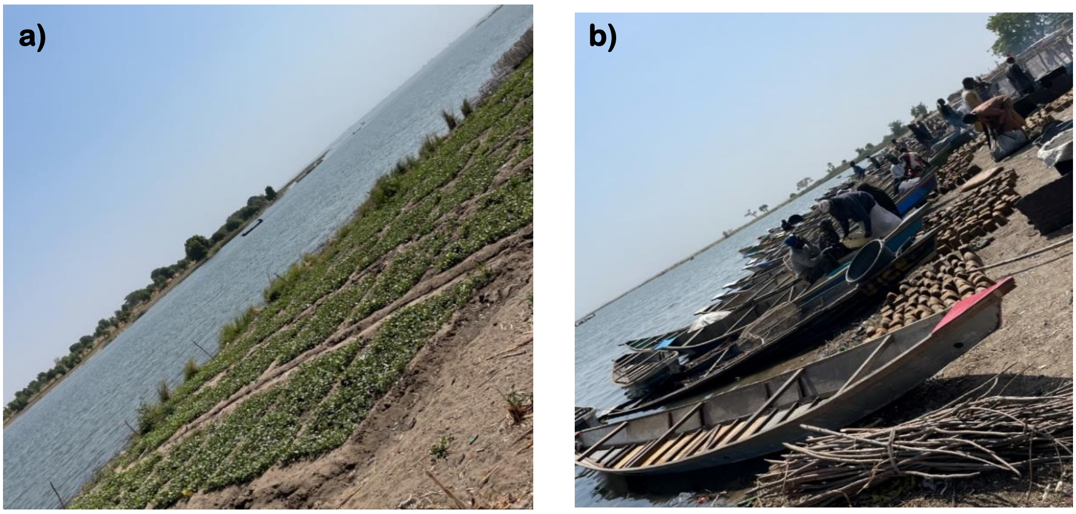


Figure 7: pH and Temperature of Water in Reservoir



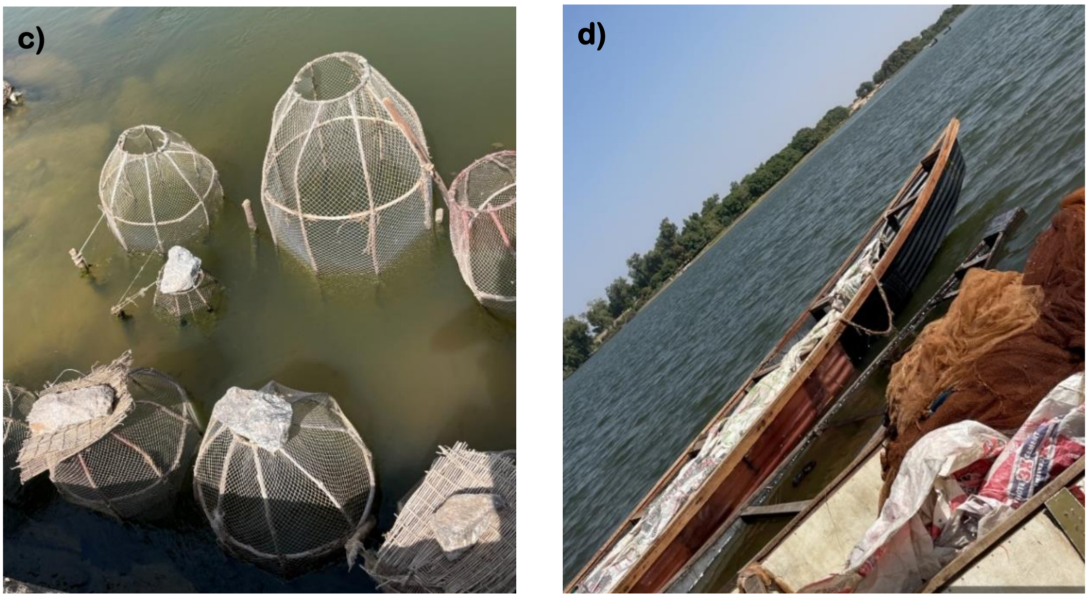


Figure 8: a) Small scale farming, b) Bricks making and fish smoking activities, c) Small scale continuous fishing practices, d) Large scale continuous fishing practices.

3.2 Discussion

3.2.1 Sedimentation's Impact on Dam Capacity and Flood Risk

The sedimentation observed in the Alau Dam reservoir is a critical factor that has drastically altered its capacity and poses a significant threat to the dam's structural integrity. Since the dam became operational in 1986 with a reported design capacity of 112 million cubic meters (MCM), sediment accumulation over the years has substantially reduced the reservoir's effective water storage capacity. This reduction is not only due to the increase in water inflows driven by seasonal precipitation and may be climate change but also because of the absence of sediment management strategies and regular maintenance from 1986 to 2022. As a result, the dam is increasingly unable to manage the water inflows it currently receives. The sediment build-up has led to the expansion of the reservoir's surface area, distorting the volume calculations derived from empirical surface-area-volume relationships. Calculated volumes of 296 MCM and 279 MCM, based on these formulas, suggest that the reservoir has experienced a substantial increase in capacity. However, this perceived expansion is misleading, as it is driven by the displacement of water by accumulated sediment rather than an actual increase in water volume. Similar phenomena have been observed in other systems, such as the Mara wetland in East Africa, where sediment displacement has caused an apparent expansion of surface area without corresponding increases in water storage (Bregoli et al., 2019).

The expansion of the reservoir's surface area due to sediment accumulation introduces serious risks for the dam's overall stability. As sediments accumulate and displace water, the space available for water storage diminishes. Consequently, during periods of high inflow, such as major flood events, the reservoir cannot effectively accommodate the excess water. This reduction in capacity forces more water toward the upper levels of the dam, increasing the likelihood of overtopping. While the crest of the dam is designed to handle overflow during extreme events, the expansion of the reservoir due to sediment accumulation heightens the risk of water spilling not only over the crest but also over the earthen embankments that surround the dam.

Earthen embankments, in particular, are vulnerable to erosion compared to concrete structures. As the water level rises due to the displaced volume, it may not only spill over the designed crest but also over weaker sections of the dam, particularly at the junction where the concrete structure meets the earthen embankment. This junction is a common weak point in dam structures, and the increased hydraulic pressure from displaced water can lead to significant erosion of the earthen material. Once erosion begins, it can create channels through the embankment, progressively weakening the dam's structure.

The progression of erosion at these vulnerable points can rapidly escalate, especially if the dam experiences sustained overtopping. Water flowing over the crest and into the embankments accelerates the erosion process, gradually washing away the soil and sediment that form the core of the earthen walls. This erosion can create cavities and voids within the embankment, further undermining the structural integrity of the dam. If the erosion reaches a critical point, it could lead to a complete collapse of the earth walls, causing a catastrophic failure of the dam.

In the event of such a failure, the dam would no longer be able to retain the reservoir's water, resulting in a sudden and uncontrolled release of water downstream. This type of failure is particularly dangerous because it occurs rapidly and with little warning, leaving downstream communities at significant risk of severe flooding. Additionally, the collapse of the earthen embankment would likely compromise other structural components of the dam, including the spillway, exacerbating the overall damage and leading to widespread downstream devastation. This potential for dam failure due to sediment displacement and overtopping is further exacerbated by the lack of sediment management at the Alau Dam. Without interventions such as dredging or sediment removal, the sediment build-up will continue to reduce the reservoir's capacity and increase the risk of overtopping and erosion during future flood events. The absence of proactive sediment management measures raises concerns about the dam's long-term sustainability and its ability to continue functioning safely and effectively.

The increased flood risks associated with sedimentation are well-documented in global studies. Mobasher (2020) found that sedimentation in Egyptian reservoirs significantly reduced their storage capacities and increased flood risks. Similar findings have been reported in other African dams, where sediment deposition has contributed to hydraulic failures during peak inflows (Saruchera & Lautze, 2019). In the case of the Alau Dam, the ongoing sediment accumulation, without corresponding sediment management interventions, raises alarms about both its operational capacity and its structural safety. Unchecked sedimentation can lead to reduced storage capacity, changes in water quality, and the disruption of downstream ecosystems. Furthermore, the dam's ability to regulate inflows, provide water for supply and irrigation, and prevent floods is progressively being undermined by the accumulation of sediment. The absence of sediment management and proactive maintenance significantly heightens the risks posed by sedimentation, threatening the dam's intended purpose and putting both the structure and downstream communities at risk of catastrophic failure. Gharehkhani (2011) and Fripp et al. (2020) highlighted that sedimentation often elevates hydraulic pressures on aging infrastructure, exacerbating the risk of dam failure, particularly in the absence of regular maintenance.

3.2.2 Operational Inefficiencies and Management Failures

The operational management practices of the Alau Dam have played a critical role in exacerbating recurring flood events and imposing additional pressures on the dam's infrastructure. In particular, the delayed and inflexible water release strategy currently employed is inadequate for managing the dynamic inflows the dam experiences during seasonal rainfall periods. The practice of opening the sluice gates for a continuous three-month period, typically beginning when the water level reaches a critical threshold, is neither sustainable nor effective in balancing reservoir water levels with downstream flood prevention.

The delayed release of water from the Alau Dam significantly impacts downstream areas, resulting in increased flood risks for communities living along the Ngadda River. By waiting until the reservoir reaches near-capacity levels before initiating water release, the dam management allows for an excessive accumulation of water, which increases the probability of sudden and large-scale releases. When the sluice gates are eventually opened, the large volume of water discharged over a short period creates a surge that often overwhelms downstream rivers, leading to flooding in nearby communities. This mismanagement has been observed in similar situations globally, where poorly timed water releases from dams have contributed to severe downstream flooding (Devi et al., 2021).

Beyond flooding, the delayed release also builds additional pressure on the dam walls. As water accumulates to near-capacity levels, the hydraulic pressure exerted on the dam's structure, including the walls and spillway, increases significantly. This elevated pressure can exacerbate structural weaknesses, particularly in aging dams like Alau, where maintenance and upgrades have been insufficient. The prolonged exposure of the dam walls to this intense pressure increases the risk of structural failures, including cracking and erosion of key components. Chanson & James (1999) have shown that excessive hydraulic loads on dam walls, particularly when sustained over time, can lead to material fatigue and potential failures, especially in older concrete and earthen structures.

Fluixá-Sanmartín et al. (2018) highlight the importance of adaptive management strategies for dam operations, particularly in regions with seasonal rainfall patterns. Adaptive management involves the continuous monitoring of reservoir levels, rainfall forecasts, and downstream conditions to inform more flexible and timely water release decisions. Such strategies could allow the Alau Dam to mitigate flooding risks more effectively by releasing smaller volumes of water more frequently rather than waiting for a critical threshold to be reached. This approach would not only reduce downstream flooding but also alleviate the hydraulic pressure on the dam walls, thus enhancing the structure's overall stability and longevity. Research by Saavedra Valeriano et al. (2010) supports the need for dynamic and responsive water management in dams situated in flood-prone regions. In their study of dam operations, the authors found that flexible water release practices, tailored to weather forecasts and real-time monitoring of reservoir inflows, helped to minimize the occurrence of catastrophic floods downstream while reducing the stress on dam structures.

In the case of the Alau Dam, the rigid operational practices have clearly contributed to both structural vulnerabilities and increased flood risks. The failure to adopt adaptive management strategies, where water releases are based on inflow forecasts and reservoir dynamics rather than fixed schedules, has led to unpreventable flooding events downstream and placed unnecessary strain on the dam itself. By allowing water levels to reach critical thresholds before initiating releases, the dam management has effectively set the stage for both structural degradation and hazardous downstream conditions.

Therefore, a shift toward adaptive management practices is crucial for improving both the safety and functionality of the Alau Dam. More frequent, smaller-scale water releases based on predictive hydrological models and real-time data could alleviate the pressure on the dam walls, prevent flooding downstream, and reduce the risk of long-term structural damage. Without these changes, the dam will continue to face unnecessary stress, heightening the probability of future operational failures and the potential for catastrophic flooding events.

3.2.3 Structural Failures and Aging Infrastructure

The physical state of the Alau Dam is another significant risk factor that could lead to its failure. The partial collapse of the spillway and the near-collapse of the dam crest indicate severe structural degradation, likely exacerbated by the forces of water flow and erosion at the dam's foundation. Studies by Larrauri et al. (2020) have shown that aging dams, especially those without regular maintenance, are prone to structural failures under increased hydrological loads. Poor infrastructure maintenance, combined with sedimentation, has resulted in increased hydraulic stress on the dam, making it more vulnerable to failure during peak inflow periods. This is consistent with findings by Mallakpour et al. (2019), who noted that the lack of infrastructure upgrades and regular maintenance often leads to dam failures, particularly in older dams that were not designed to withstand current hydrological stresses.

3.2.4 Environmental Degradation and Lack of Ecological Consideration

The absence of environmental flow considerations in the dam's operation has had significant adverse effects on the surrounding ecosystems. Downstream ecosystems that rely on consistent water flows have been severely impacted, with ecological degradation evident along the Ngadda River. Olden & Naiman (2010) emphasize the importance of maintaining environmental flows to sustain healthy ecosystems downstream of dams, a practice that is often neglected in dam management. The unsustainable fishing practices and pollution from upstream agricultural activities further compound the environmental damage. These issues have been observed in other African reservoirs, where the lack of environmental flow considerations and poor enforcement of land use policies have led to widespread ecological degradation (Chunga et al., 2022). This imbalance between infrastructure operation and ecological sustainability must be addressed to prevent further environmental harm.

3.2.5 Combined Impacts and Systemic Failure

The hydraulic failure of the Alau Dam over the years and particularly in 2022 is not attributable to any single factor but rather to the interaction of several systemic issues. Sedimentation, poor operational management especially delayed release of water, aging infrastructure and may be climate change have all combined to overwhelm the dam's capacity and lead to recurrent flood events. These findings echo the conclusions of Alvi & Alvi (2023), who argue that dam failures are often the result of multiple interconnected factors, including environmental changes and management practices. The absence of a comprehensive and adaptive management approach has allowed these issues to persist and compound, resulting in a systemic failure of the dam's operations. Addressing these issues will require coordinated efforts, including sediment removal, infrastructure upgrades, improved water release planning, and the incorporation of environmental flows into dam management. Without such interventions, the risk of future catastrophic failures remains high, a concern highlighted by numerous studies on the sustainability of water infrastructure in developing regions (Richter & Thomas, 2007; Ho et al., 2017).

3.3 Limitations

This study has some limitations that should be considered when interpreting the findings. Firstly, the study was limited by the availability of data. This limitation affected the accuracy and completeness of the analysis and findings, particularly in areas such as sedimentation rates and environmental flows. Secondly, the study relied heavily on secondary data sources, which may not have been comprehensive enough to capture all the complexities of the reservoir system. Thirdly, there was limited field data collected, which could have provided a more robust understanding of the ecosystem dynamics. Finally, the study's limited scope focused only on the management and operation of the reservoir without considering broader socio-economic and political factors that may be influencing the management of the dam. A more holistic approach that incorporates these factors could provide a more complete picture of the challenges and opportunities for effective management of the reservoir. Despite these limitations, the study's findings provide valuable insights into the current management and operation of the reservoir, which can be used to inform future policy and management decisions.

3.4 Implication for Management

The Alau Dam faces critical issues related to sedimentation, poor operational practices, aging infrastructure, and environmental degradation, which require comprehensive management solutions. Key management actions include implementing routine dredging and a long-term sediment management plan to restore the reservoir's capacity and reduce flood risks. Transitioning to adaptive water release strategies with real-time monitoring would help alleviate downstream flooding and reduce pressure on the dam's infrastructure. Prioritizing maintenance and upgrades, particularly in vulnerable areas like the spillway and embankments, along with regular inspections, is essential to prevent structural collapse. Incorporating environmental flows into water release schedules and enforcing land-use and pollution policies will protect downstream ecosystems and ensure sustainability. Additionally, training dam operators in adaptive management, collaborating with experts, and developing a comprehensive, integrated management plan that addresses sedimentation, aging infrastructure, and climate resilience will enhance long-term sustainability. Finally, improving flood mitigation infrastructure and establishing contingency plans for emergencies such as overtopping or dam failure will protect lives and property in the event of a disaster.

4. CONCLUSION

The study has revealed critical issues affecting the Alau Dam, primarily driven by sedimentation, poor operational management, aging infrastructure, and environmental degradation. Over time, sediment accumulation has drastically reduced the dam’s effective capacity, distorting water volume calculations and increasing flood risks. This has led to significant threats to the dam’s structural integrity, particularly through the heightened pressure on earthen embankments and the increased likelihood of overtopping during major inflow events. Without effective sediment management, these risks will continue to escalate, compromising the dam’s long-term sustainability and safety. Furthermore, the delayed and inflexible water release strategies currently employed have exacerbated downstream flooding and placed unnecessary pressure on the dam's walls, increasing the probability of structural failure. The lack of adaptive water release practices, combined with insufficient monitoring and reactive management approaches, has created conditions that heighten both operational inefficiencies and structural vulnerabilities. The aging infrastructure, particularly the spillway and embankments, is increasingly susceptible to failure due to prolonged exposure to excessive hydraulic pressure and erosion. The environmental degradation caused by insufficient environmental flow considerations has had severe impacts on downstream ecosystems, compounding the dam’s challenges. A lack of policy enforcement around land use and unsustainable practices has further exacerbated pollution and ecological damage in the Ngadda River. The hydraulic failure of the Alau Dam is the result of multiple interconnected factors, including sedimentation, poor management practices, and climate-related hydrological stresses. Addressing these issues requires a comprehensive and adaptive management approach, including sediment removal, regular infrastructure maintenance and upgrades, dynamic water release strategies based on real-time data, and the integration of environmental flow considerations. Without these interventions, the risk of future catastrophic failures remains high, threatening the safety of downstream communities and undermining the dam’s intended purposes.

5. RECOMMENDATIONS

The following recommendations are designed to mitigate risks, improve dam operations, and ensure the long-term sustainability of the Alau Dam while addressing the critical issues of flooding, sedimentation, and infrastructure management:

1. **Flexible Water Release Policy:** The current frequency and timing of water release from the Alau Dam reservoir contribute significantly to downstream flooding. It is crucial to develop a comprehensive water release policy informed by hydrological and hydraulic modelling. This policy should ensure controlled and regulated water releases that consider the downstream river capacity and ecological factors, thereby minimizing flood risks and promoting environmental sustainability.

2. **Sediment Management Strategies:** Sediment deposition in the Alau Dam reservoir has a significant impact on its capacity and longevity. The implementation of sediment management strategies such as regular dredging, sediment flushing, and possibly silt traps should be prioritized to maintain the reservoir's operational efficiency and extend its lifespan. These strategies should be part of a long-term sediment management plan that is periodically evaluated for effectiveness.

3. **Infrastructure Maintenance and Upgrades:** Urgently reinforce aging infrastructure, particularly the spillway and earthen embankments, to prevent collapse during peak inflow periods. A regular maintenance schedule should be established, with periodic inspections of vulnerable areas such as the junction between concrete structures and earthen embankments.

4. **Secondary and Tertiary Storage Structures:** To manage surplus water and reduce the volume flowing downstream, the dam infrastructure should be upgraded to include secondary and tertiary water storage structures. A cascading dam system with multiple ponds and canals is recommended to store surplus water. This would help capture and store water during high inflow periods, reducing flood risks and providing additional resources for agricultural use and possibly small-scale hydropower generation.

5. **Monitoring and Evaluation Mechanisms:** The effectiveness of these proposed solutions and the overall management practices at the Alau Dam should be regularly monitored and evaluated. This can be achieved through the implementation of robust monitoring and evaluation mechanisms, including regular inspections, performance assessments, and the establishment of feedback loops. Continuous monitoring will allow for timely interventions, adaptive management, and improvement of the dam's operational efficiency and safety.

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