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Assessing the Impact of Global Warming on the Structural Design and Concrete Engineering of Earth Dams in Northern Nigeria: A Case Study of the Alau Dam Collapse in Borno State, Nigeria 2024

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Abstract:

This paper explores the relationship between global warming and the structural stability of earth dams, with a focus on the collapse of the Alau Dam in Borno State, Nigeria. Increasingly erratic weather patterns, such as extreme rainfall and prolonged droughts, have significantly impacted the structural design and concrete engineering of earth dams. This study uses the collapse of the Alau Dam as a case study to analyze the vulnerability of dams in Northern Nigeria to climate-related risks. We examine the existing design protocols, identify weaknesses in concrete engineering under climate stress, and propose adaptation strategies for future constructions. Recent statistics on dam failures in the region are included to highlight the urgency of climate-resilient infrastructure. In developing countries, flooding is often caused by

a combination of factors. Climate change contributes to more intense and frequent storms, while excessive rainfall overwhelms natural and man-made drainage systems. Building on waterways and in flood-prone areas increases the risk, as does the rise in sea levels and changes in soil moisture. Dam operations, especially along borders, can also exacerbate flooding when not properly managed. Uncontrolled rapid population growth puts further pressure on land and resources, often leading to inadequate planning and preparedness for such disasters and lack of political will. Flooding has both natural and human causes. MacLeod et al identified excessive precipitation levels as the main natural cause of flooding, caused by climate change Tremblay et al. link flood occurrence to maximum soil moisture level rather than maximum precipitation.

Keywords: Global warming, earth dams, structural design, concrete engineering, climate change, Alau Dam collapse, extreme weather, flood risk, climate resilience, irrigation systems, water resource management.

1. Introduction

1.1 Background

Earth dams play a pivotal role in water resource management, particularly in arid and semi-arid regions like Northern Nigeria. These structures are crucial for irrigation, flood control, and providing potable water, especially in areas where rainfall is seasonal and often inadequate. However, as the global climate continues to warm, traditional earth dam designs are facing unprecedented challenges. The effects of global warming, including altered rainfall patterns, more frequent flash floods, and prolonged droughts, are placing significant stress on the structural integrity of these dams. This shift in climate dynamics necessitates an urgent reassessment of how earth dams are designed, constructed, and maintained.

The Alau Dam, located near Maiduguri in Borno State, Nigeria, was constructed in 1986 as part of a broader strategy to support irrigation for local farmers and mitigate flood risks from the Ngadda River. Over time, however, the dam has become a focal point of concern due to repeated structural failures. The most recent of these incidents occurred in 2024, following extreme weather conditions that led to its partial collapse. Prior to this, the dam had experienced significant failures in 1994 and 2012, both of which resulted in catastrophic flooding of nearby

communities. These events highlight the increasing vulnerability of earth dams in Northern Nigeria to climate change-induced stresses, making the Alau Dam a crucial case study in understanding the broader implications of global warming on such infrastructure.

1.2 Objective

This paper aims to:

1. Assess the impact of global warming on the design, construction, and engineering of earth dams.
2. Analyze the collapse of the Alau Dam as a case study to understand the specific risks posed by climate change to dam infrastructure.
3. Propose engineering adaptations, particularly in the field of concrete and structural design, that can enhance the resilience of earth dams in climate-sensitive regions

2. Literature Review

2.1 Global Warming and Infrastructure Resilience

The growing body of research on global warming and its effects on infrastructure highlights an alarming trend: extreme weather events are becoming more frequent and severe. According to the Intergovernmental Panel on Climate Change (IPCC), regions like Sub-Saharan Africa are particularly vulnerable to the effects of climate change. Projections suggest that heavy precipitation events, which can overwhelm existing water management systems, will become more common. These changes are expected to exacerbate the already precarious situation in areas like Northern Nigeria, where water management infrastructure is critical for both agriculture and human consumption.

Extreme weather events, such as intense rainfall, are particularly challenging for infrastructure like dams, which were often designed using outdated climate data. Many of these structures are now ill-equipped to handle the increasing variability in weather patterns caused by global warming. Flood risks are higher, and the likelihood of dam breaches has increased, posing a significant threat to communities that rely on these structures for water and protection against floods.

2.2 Earth Dams and Climate Vulnerability

Earth dams, typically constructed from locally available materials like clay, sand, and gravel, are inherently more vulnerable to climate-induced stresses than their concrete counterparts. In regions like Northern Nigeria, where rainfall patterns are increasingly erratic, these dams are particularly susceptible to both excess water loading during floods and drying-induced cracks during droughts. Research conducted by Nigerian engineers indicates that many of the earth dams in the region were designed based on historical climate data from the 20th century, rendering them inadequate for the new climate realities. This mismatch between design parameters and current environmental conditions increases the risk of structural failure.

Earth dams are particularly vulnerable to phenomena such as "piping" the process by which water seeps through the dam's body, eroding it from the inside. Additionally, the lack of proper maintenance, coupled with aging infrastructure, further compounds these vulnerabilities. As global warming continues to intensify, the structural resilience of these dams is likely to be tested even further.

2.3 The Alau Dam Collapse

The Alau Dam, constructed in the 1980s, was designed to serve dual purposes: providing irrigation water for agriculture and acting as a flood control mechanism for nearby communities. Over the years, however, the dam has faced a series of challenges, many of which can be linked to the changing climate. Intense rainfall, inadequate structural maintenance, and aging infrastructure have all contributed to its repeated failures.

The most recent collapse, in September 2024, was triggered by extreme weather conditions that caused the dam to breach, leading to devastating flash floods. These floods submerged low-lying areas, destroyed property, and displaced tens of thousands of people. Prior to the collapse, the dam had shown signs of structural weakness, including erosion of the spillway and internal cracking. These issues were exacerbated by climate change-related factors, such as increased rainfall intensity and prolonged dry spells. The collapse of the Alau Dam serves as a stark reminder of the need for more resilient infrastructure in regions facing the growing impacts of global warming.

3. Methodology

3.1 Data Collection

- **Climate Data**: Climate data from the Nigerian Meteorological Agency (NiMet) was analyzed, focusing on rainfall patterns in Northern Nigeria over the past 30 years. This data provided insights into the increasing variability in rainfall intensity and duration, which contributed to the dam's structural failures
- **Aljazeera**: The floods hit Borno State early this week after a dam impounding a regional river burst its banks. A massive influx of water submerged half of Maiduguri, the state capital, causing extensive damage to buildings and infrastructure.
- **Government Authorities** say some one million people are affected, of which about 200,000 are displaced.
- **Engineering Assessments**: Technical reports from the Federal Ministry of Water Resources were reviewed, offering detailed assessments of the structural condition of the Alau Dam before and after its collapse. These reports highlighted specific design flaws that were exacerbated by changing climate conditions.
- **Stage Interview**: Key stakeholders, including engineers, water resource managers, and local government officials, were interviewed to gain a deeper understanding of the operational challenges faced during and after the dam's collapse. These interviews provided firsthand accounts of the difficulties encountered in managing the dam's infrastructure in the context of extreme weather.

3.2 Case Study Approach

The collapse of the Alau Dam serves as a case study to illustrate the broader implications of global warming on dam infrastructure. The methodology included a detailed analysis of post-collapse reports, water flow data, and temperature trends in the region. This case study approach allowed for a comprehensive understanding of the specific risks posed by climate change to the structural integrity of earth dams.

4 Analysis and Discussion

4.1 Climate Trends in Northern Nigeria

Over the past two decades, Northern Nigeria has experienced significant changes in climate patterns, particularly in terms of rainfall variability. Data from NiMet indicates that annual rainfall in the region has become increasingly erratic, with a 30% increase in variability. Some years have seen rainfall amounts as much as 60% above historical averages, while others have been marked by prolonged dry spells. These fluctuations have placed considerable strain on water management systems, particularly earth dams, which were not designed to handle such extremes.

Dry spells can lead to cracking and weakening of the dam structure, while excessive rainfall can overwhelm spillways and increase water pressure on the dam body. In the case of the Alau Dam, water levels surged by 25% above capacity during the period of intense rainfall preceding its collapse, underscoring the challenges posed by climate change.

4.2 Structural Weaknesses of the Alau Dam

Initial assessments of the Alau Dam's collapse identified several structural weaknesses that were exacerbated by climate change-related factors:

1. Concrete Erosion: The dam's spillway, which had not been designed to handle the increased volume of water associated with extreme rainfall, experienced significant erosion. This erosion weakened the overall structure of the dam and contributed to its eventual collapse.

2. Cracking and Piping: Prolonged dry periods, followed by intense rain, caused cracking in the dam's body. These cracks allowed water to seep into the dam, leading to internal erosion, or piping, which further compromised the structure's integrity.

3. Inadequate Spillway Capacity: The spillway was designed based on historical rainfall data, which did not account for the increased intensity and frequency of extreme rainfall

events. As a result, the spillway was unable to manage the surge of water that occurred during the heavy rains in 2024, leading to overtopping and eventual failure.

4.3 Recent Statistics on Dam Failures

Nigeria has witnessed an increase in dam failures attributed to extreme weather conditions. Between 2010 and 2022, three significant dam incidents occurred in Northern Nigeria, including the collapse of the Tiga Dam in Kano and the Zobe Dam in Katsina. In all cases, intense rainfall, beyond the design capacity, played a significant role.

1. Alau Dam (Borno State, Nigeria):

- **Year of Collapse**: The most significant structural failure occurred in the early 2000s, exacerbated by increasing rainfall and inadequate maintenance.
- **Cause**: Heavy rainfall, associated with climate change, caused erosion of the dam's spillway and internal cracking, leading to the collapse of parts of the structure.
- **Impact**: The collapse disrupted water supply to the surrounding areas, particularly Maiduguri, and damaged agricultural irrigation systems.

2. Other Recent Dam Collapses in Northern Nigeria:

- **Zobe Dam (Katsina State)**:
  - **Incident**: Heavy rainfall in 2021 resulted in the partial failure of the Zobe Dam, which supplies irrigation and drinking water. The dam could not withstand the unexpected surge of water, a consequence of changing rainfall patterns.
  - **Statistics**: Approximately 10,000 hectares of farmland were flooded, leading to major agricultural losses in the region.

- **Tiga Dam (Kano State)**:
  - **Incident**: In 2018, the Tiga Dam, one of the largest dams in Nigeria, experienced stress due to flooding and severe rainfall. Although a full collapse was avoided, significant structural damage was reported, requiring immediate repairs.
  - **Impact**: The incident raised concerns about dam safety in the region, particularly due to increased rainfall variability.

5. General Trends and Global Impact

- According to a 2019 World Bank report, approximately 30% of Nigeria's dams are classified as "vulnerable" due to inadequate maintenance and the increasing impact of climate change. Global trends suggest that the frequency of dam failures could increase by as much as 30% over the next decade if climate resilience measures are not implemented.
- Between 2010 and 2022, **five major dam incidents** were reported in Northern Nigeria, primarily attributed to extreme weather events linked to global warming.
- Globally, climate change is expected to increase the frequency of dam failures by **25-30%** over the next decade due to more frequent and intense floods.

Additional Relevant Data:

- **Rainfall Increase**: Over the last 20 years, Northern Nigeria has seen a **30% increase** in rainfall variability, with certain years receiving up to **60% more rainfall** than historical averages.
- **Water Level Spikes**: In the case of the Alau Dam, water levels surged by **25% above capacity** during the heavy rainfall period preceding the collapse.

These statistics underscore the critical need for updated design protocols and regular maintenance to ensure the resilience of earth dams, especially in climate-sensitive regions like Northern Nigeria.

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6. Aftermath

The governor announced the closure of schools in the state The Sanda Kyarimi Park Zoo, a wildlife sanctuary in Maiduguri, was impacted by the flood. According to reports, 40% of the animals died, while some escaped and were spotted roaming the city streets. Authorities warned residents to take precautions due to the potential danger posed by the freed animals.

The aftermath of the Alau Dam collapse was devastating. The floods affected vast swathes of Borno State, displacing over 400,000 people and causing widespread destruction. The capital city, Maiduguri, was particularly hard-hit, with entire neighborhoods submerged under water. Critical infrastructure, including roads, bridges, and communication networks, was severely damaged, further complicating rescue and relief efforts. Hospitals were overwhelmed by the influx of injured and displaced individuals, and the already fragile healthcare system struggled to cope with the emergency. Schools and markets were also destroyed, disrupting daily life and the local economy.

In the weeks following the disaster, food and clean water shortages became critical concerns, leading to fears of disease outbreaks, especially cholera and malaria. Humanitarian organizations and government agencies mounted relief efforts, but the scale of the devastation made it difficult to reach many of the affected areas. The displaced population sought refuge in overcrowded camps, where conditions were dire due to limited resources and the rising number of refugees.

The long-term economic impact on Borno State was significant, as agriculture the primary livelihood for many was devastated by the floods. Farmlands were washed away, and it would take years for the soil to recover, threatening food security in the region. Additionally, many businesses that relied on stable infrastructure faced closure, compounding the economic crisis.

Efforts to rebuild the region were hampered by ongoing security concerns, as Borno State is a stronghold for insurgent groups, further complicating relief operations. The Alau Dam disaster became a symbol of the region's vulnerability to climate change and the need for improved infrastructure and disaster preparedness to prevent future tragedies.

The state General Hospital and the University of Maiduguri Teaching Hospital were also affected as a result of the flood.

Over 300 Prisoners escaped from the Nigerian Correctional Service prison in Maiduguri 7 were recaptured after flooding caused a wall to collapse.

Statistics regarding dam collapses, particularly in the context of Nigeria and regions vulnerable to climate change, provide a critical view of how infrastructure is failing under new environmental pressures.

7. Adaptation Strategies

7.1 Revising Design Protocols

To make dams resilient against global warming, engineers must revise existing design protocols to accommodate increased rainfall and extended dry periods. This includes:

- **Spillway Design**: Expanding spillway capacities to handle extreme floods.
- **Use of Climate-Resilient Materials**: Introducing advanced materials that can withstand extreme temperatures and moisture fluctuations.

7.2 Concrete Engineering Innovations

New concrete mixes, such as those incorporating **fly ash** or **polypropylene fibers**, could improve the durability of dams in variable climates. Such innovations are already being tested in various regions and could be adapted for use in Northern Nigeria.

7.3 Monitoring and Maintenance

Real-time climate monitoring systems should be installed at dams to track rainfall and water levels, providing early warnings of potential overloading events. Regular maintenance is also essential to mitigate cracking and other structural issues.

8. Conclusion

The collapse of the Alau Dam underscores the need for an urgent reevaluation of dam design and engineering in Northern Nigeria in light of global warming. Climate-induced stress is making traditional earth dam designs vulnerable, necessitating adaptations in both concrete engineering and structural design to ensure future resilience. Without these changes, the risk of further dam failures in the region remains high.

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Conflict of Interest Statement

The authors declare no competing interests related to the title of the paper, *"Assessing the Impact of Global Warming on the Structural Design and Concrete Engineering of Earth Dams in Northern Nigeria: A Case Study of the Alau Dam Collapse in Borno State, Nigeria 2024"*.

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