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Research Article

Design Challenges and Water Harvesting Performance of Small Dams in Sudan (2010–2019)

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Abstract

Water harvesting (WH) is a critical strategy for addressing water scarcity in arid and semi-arid regions, where communities rely on limited rainfall to sustain domestic supply, livestock, and agricultural production. This study evaluates the design, construction, and operational performance of small water-harvesting dams constructed in Sudan between 2010 and 2019. A basin-based analytical framework was applied to describe hydrological conditions and manage uncertainties inherent in data-scarce environments. The methodology integrates regional and empirical flood-estimation techniques with assessment of key design parameters, evaluation of construction practices, and qualitative risk analysis. Results indicate that, despite their relatively small size, these dams face engineering challenges comparable to larger dams, particularly in terms of hydrological uncertainty, seepage control, reservoir tightness, and limited site-investigation data. The absence of continuous hydrometric records complicates flood-frequency analysis and spillway design, increasing uncertainty and operational risk. The study underscores the importance of incorporating risk-informed design approaches and strengthening hydrological and geotechnical investigations to enhance safety, functionality, and long-term performance of small dams in Sudan. Additionally, it highlights the need for systematic monitoring and adaptive management strategies to mitigate extreme events, optimize water utilization, and support sustainable rural development in dryland regions increasingly affected by climate variability and growing water demand.

Keywords

Small Dams, Water Harvesting, Sudan, Hydrological Uncertainty, Seepage, Dam Safety

1. Introduction

Sudan is predominantly characterized by extensive arid and semi-arid regions, where rainfall is highly variable, sporadic, and often insufficient to sustain domestic water supply, agricultural production, and livestock management [1, 2]. These climatic constraints have historically resulted in chronic water scarcity, which imposes significant limitations on socio-economic development, food security, and rural livelihoods [3, 4]. In response, water harvesting (wh) strategies have been increasingly adopted as cost-effective solutions to capture, store, and regulate seasonal surface runoff. Among these strategies, small dams are recognized as essential infrastructure for improving water availability, providing reliable storage for irrigation, supporting livestock needs, and enhancing overall resilience to climatic variability in rural communities [5-7].

Between 2010 and 2019, a considerable number of small

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dams were constructed across Sudan under national and regional development initiatives aimed at strengthening water security and promoting sustainable resource management [3]. Despite their relatively modest dimensions compared to large-scale reservoirs, these structures serve as critical components of local hydrological systems. Their planning, design, and operation, however, are often constrained by limited hydrological and geotechnical information, inadequate site investigations, and budgetary limitations [8, 9]. These constraints introduce substantial uncertainty in critical design considerations, including flood estimation, spillway sizing, seepage control, and reservoir efficiency, which may compromise dam safety and performance [10].

While prior studies have primarily focused on the socio-economic and agricultural benefits of small dams [4, 5, 7], systematic assessments of the engineering and hydrological challenges associated with data-scarce environments remain limited. This study addresses this gap by evaluating the design, construction, and operational performance of small dams in Sudan, with particular emphasis on hydrological uncertainty, seepage management, and risk-informed decision-making.

2. Research Problem and Objectives

Research Problem

Although small dams are commonly perceived as structurally simpler and less risky than large dams due to their lower height and reduced hydrostatic pressures [9], they remain subject to significant hydrological and geotechnical uncertainties [8]. In Sudan, the lack of streamflow gauging stations and long-term hydrometric records complicates flood estimation and risk assessment. Consequently, designers must rely on regional empirical methods and short rainfall records, increasing uncertainty in spillway design, seepage control, and reservoir performance [1].

3. Study Area and Background

Sudan exhibits a wide range of climatic conditions, extending from hyper-arid desert regions in the north to semi-humid zones in the south [2]. The majority of small dams constructed between 2010 and 2019 are situated within dry and semi-dry catchments, where surface water availability is highly limited and strongly seasonal [1]. Rainfall in these areas typically occurs in short, intense events, producing ephemeral runoff within seasonal wadis [10].

Catchment characteristics in these regions commonly include shallow soil profiles, exposed or fractured bedrock, and highly permeable geological formations [11, 12]. Such geomorphological and geological conditions exert a significant influence on hydrological responses, including runoff generation, seepage dynamics, sediment transport, and reservoir storage efficiency [10].

4. Methodology

4.1. Hydrological Analysis

Catchment characteristics were analysed using available topographic, rainfall, and geological information. Runoff and flood discharges were estimated using regional flood equations and empirical methods commonly applied in data-scarce regions [1, 2]. The uncertainty associated with the absence of continuous streamflow records was qualitatively assessed.

4.2. Quantitative Design Assessment

Key design parameters, including reservoir capacity, spillway discharge capacity, and seepage control measures, were reviewed based on available design documents and reports [5] Mathematical relationships and comparative indicators were used to evaluate design adequacy and conservatism.

4.3. Construction Process Assessment

Construction practices, material selection, and quality control procedures were reviewed to identify potential deficiencies affecting dam performance [12].

4.4. Comparative Risk Analysis

The risks associated with small dams were compared with those of large dams, focusing on hydrological uncertainty, failure modes, operational performance, and socio-economic consequences [10].

5. Results and Discussion

5.1. Hydrological Uncertainty

The analysis confirms that the lack of hydrometric monitoring stations is a major constraint in the design of small dams in Sudan. Designers frequently rely on short rainfall records, regional equations, and indirect estimation techniques, resulting in significant uncertainty in flood frequency analysis and spillway design.

5.2. Structural and Geotechnical Considerations

Although small dams are subjected to lower hydrostatic pressures than large dams, seepage remains a critical issue. Limited budgets often restrict detailed geological and geotechnical investigations, increasing the likelihood of seepage losses and reduced reservoir efficiency. In several cases, insufficient foundation treatment and cutoff measures were identified as key contributors to long-term water loss.

5.3. Risk Perspective

The findings indicate that small dams can pose risks comparable to those of larger dams, albeit with different consequences [9]. While the probability of catastrophic failure is generally lower, chronic risks such as seepage losses, rapid sedimentation, and underperformance are more prevalent.

6. Conclusions

The study of small dams constructed in Sudan between 2010 and 2019 reveals several critical insights regarding their hydrological and geotechnical performance:

(1) design complexity: small dams, despite their modest size, face engineering challenges comparable to large dams.

(2) hydrological data limitations: the absence of continuous and reliable hydrometric records significantly affects flood estimation and spillway design.

(3) seepage and reservoir integrity: effective seepage control is essential for maintaining long-term water retention and structural performance.

(4) risk-informed design necessity: incorporating risk-based approaches is crucial.

(5) operational sustainability: careful planning and adaptive management are required.

7. Recommendations

Based on the study's findings, the following recommendations are proposed to improve the planning, design, and operational performance of small dams in Sudan:

Establish and maintain basic hydrometric monitoring stations within small dam catchments to support accurate flood estimation and operational decision-making.

Adopt simplified, cost-effective design criteria that explicitly account for hydrological uncertainty, ensuring safety without imposing prohibitive costs.

Strengthen geological and geotechnical investigations, particularly in areas susceptible to seepage, to enhance reservoir tightness and reduce long-term water loss.

Develop national guidelines and standardized protocols for small dam planning, design, and construction to ensure consistency, reliability, and adherence to best practices.

Integrate risk assessment techniques at early stages of project planning and design to identify potential failure modes, optimize mitigation measures, and enhance resilience to extreme events.

Abbreviations

WHH	Water Harvesting
SD	Small Dams

Author Contributions

Hummam Mohammed Yousif: Data curation, Writing – original draft, Writing – review & editing

Mona Adam Gumma Rabih: Supervision

Conflicts of Interest

The authors declare no conflicts of interest.

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