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Small Dam Design and Construction for Sustainable Water Resources Management: A Comprehensive Review

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ABSTRACT

Small dams are crucial in water resource management, particularly in regions with water scarcity and climate unpredictability. Despite their cost-effectiveness, the construction of small dams often lacks engineering standards, which raises concerns about their long-term stability and safety. This study reviews the design, construction, stability, and protection of small dams, emphasizing the importance of proper site selection, geological and hydrological studies, and advanced methodologies, such as Geographic Information Systems and multi-criteria decision-making approaches in dam evaluation. Furthermore, the study highlights the significance of detailed planning, material selection, and quality construction to ensure dam longevity. It also discusses the role of modern tools, such as HEC-HMS, HEC-RAS, and GeoStudio in assessing flood risks, seepage, and stability. Inadequate design, particularly in the face of extreme weather events, can lead to dam failures, emphasizing the need for comprehensive planning and rigorous assessments. Through an analysis of various studies and case examples, this paper aims to provide insights into sustainable small dam construction and water resources management practices that ensure their effectiveness and resilience in addressing water scarcity challenges.

Index Terms: Small Dam Construction, Water Resource Management, Stability Analysis, Construction Practices, Site Selection, Hydrology

1. INTRODUCTION

Small dams and reservoirs have consistently drawn the interest of rural development authorities and aided human development by providing reliable sources of water [1], [2]. Small dams are increasingly recognized for their role in water resource management, particularly in regions facing water scarcity and unpredictable climate patterns [3].

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A "small" dam is typically defined as one where the maximum height above the original streambed does not exceed approximately 15 m (about 50 feet). In addition, it is characterized by a volume not large enough to justify the use of detailed design methods typically reserved for larger dams. Furthermore, if a low dam has a volume greater than 765,000 cubic meters, it would no longer be classified as small [4] as shown in Fig. 1, the Al Abila Dam is a small dam in Iraq's Western Desert [5].

A study of three small dams, Jawa, Kasala, and Dhok Sanday Mar, evaluated the impact of the small dams on agriculture and groundwater development in the state of Punjab in Pakistan and the analysis of inflow–outflow of the dams (Figs. 2-4) shows that if properly managed, the storage is sufficient to irrigate all the croplands within the command area [6].

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Fig. 1. Al Abila Dam [5].

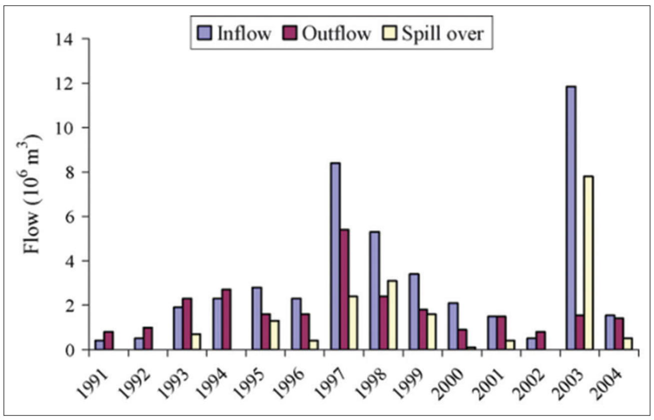

Fig. 2. Yearly inflow-out flow of Khasala dam.

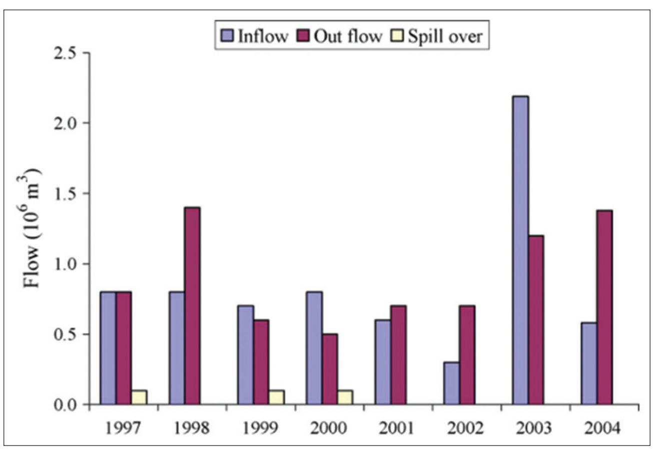

Fig. 3. Yearly inflow-outflow of Jawa dam.

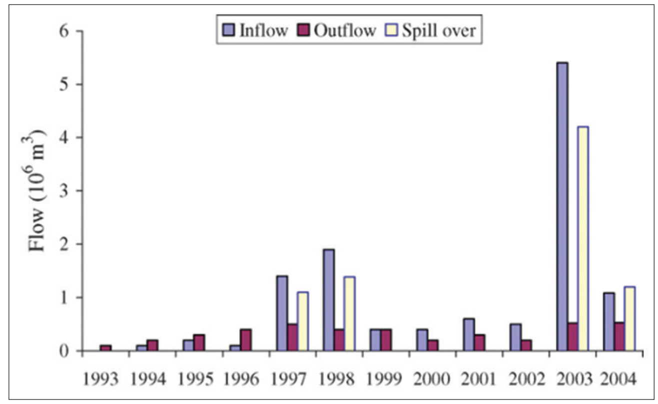

Fig. 4. Yearly inflow-outflow of D.S. Mar dam.

Salimi *et al*. highlighted the dam's crucial role in irrigation, drinking water, and industrial use in the dry, semi-arid region. The need for coordinated, long-term water management for agricultural, domestic, and industrial purposes is emphasized [7]. The construction and maintenance of small dams often pose significant challenges [8], especially when built without engineering standards. Farmers frequently construct small dams without engineering input, which raises concerns about their long-term stability, safety, and effectiveness. Valuable insights can be gained from both the successes and failures of dam applications and operations. These can guide water resource managers, policymakers, and stakeholders in achieving sustainable development goals, particularly in climate change and growing water crises [3].

Dams can be grouped differently, especially considering their height and storage; the classification can be arranged as follows:

1. Low Dams: These are usually modest in height, standing <15 m (or about 50 feet) tall. They typically don't store much water, <765,000 cubic meters, or 1 million cubic yards, making them ideal for local purposes, such as supporting irrigation or providing drinking water to nearby communities.
2. Medium Dams: Medium dams are met when a bit of height is stepped up. These range from 15 to 30 m (50–100 feet) high, have a moderate storage capacity, and are versatile. They often supply regional water needs, support agricultural irrigation, or generate hydroelectric power.
3. High Dams: High dams tower over us at more than 30 m (or around 100 feet). These giants can store large volumes of water, often reaching millions of cubic meters. They play crucial roles in significant water management projects, including large hydroelectric power stations, extensive irrigation systems, and considerable flood control.

It's worth noting that while low and medium dams focus on local or regional needs, the high dams have a much broader impact. Each type plays a vital role in water management and sustainability, tailored to specific needs based on height and storage capacity [9].

The availability of dam fill materials influenced the dam design considerably [10]. Dams can also be classified based on the construction materials used. Embankment (earthen) Dams are dams constructed with material, such as compacted soil, clay, or rockfill [11]. Rockfill dams are made of rock fragments or gravel with an impervious core from clay or concrete [12] while concrete dams are made from concrete [13].

Despite challenges, small dams are considered cost-effective solutions for water management in rural areas, especially when conventional infrastructure is not feasible. As the world faces increasing pressures from climate change, the ability of these small dams to withstand extreme weather events, such as prolonged droughts, becomes more critical [14].

Aureli *et al*. [15] reviewed several factors contributing to dam failures, including overtopping, which often results from inadequate design considerations for flood capacity, and internal erosion due to piping. They also highlighted the importance of proper management practices to mitigate risks during the design and construction phases. These factors underline the critical need for robust pre-construction assessments and planning to prevent potential failures.

This study aims to review key primary research on small dam design, focusing on aspects, such as construction, stability, safety, performance, and sustainable water management. This area has not been extensively explored. The primary studies on dam design include site selection, geological and hydrological assessments, and environmental impact evaluations. The design methodology is examined through a comprehensive approach that addresses planning, material selection, construction quality, dam height, reservoir capacity, site condition assessment, structural components, hydraulic management, earthquake risk mitigation, spillway and bottom outlet design, physical modeling, numerical simulations, sediment estimation, dam sustainability, cost, operation, and management, as well as environmental impact and community protection.

2. DAM SITE SELECTION AND PRELIMINARY INVESTIGATION

Proper site selection is the first step in ensuring the stability and effectiveness of small dams. Traditional site selection methods rely on local knowledge and experience [16]–[18]. Still, modern approaches incorporate scientific methods and tools, such as Geographic Information Systems (GIS), remote sensing (RS), and hydrological modeling, and GIS-based Fuzzy Analytic Hierarchy Process (FAHP) and Adaptive Neuro-Fuzzy Inference System (ANFIS) approaches were applied to evaluate potential dam sites, integrate environmental, hydrological, and economic factors to identify the most suitable location for mitigating water scarcity issue [19]–[24]. Appropriate site selection factors include hydrological aspects, such as runoff potential, slope, soil type, and vegetation, and socioeconomic considerations, such as proximity to communities and agricultural land [21], [25]. The design phase should also incorporate an understanding of the local geology and soil conditions [26]. The investigation process for dam construction also involves verifying the quality and quantity of fill materials to confirm their properties [10]. The decision-making methods for optimizing dam site selection were also used, emphasizing a structured approach to evaluating potential reservoir locations based on various measurable characteristics [27], [28]. Hashim and Sayl explored methodologies for selecting dam construction and rainwater harvesting. The study utilized GIS techniques, employing the weighted linear combination (WLC) and Boolean overlay methods. By assigning scores and weights, WLC analyzed parameters, such as runoff depth, slope, soil texture, land use and land cover (LULC), and proximity to irrigated lands, roads, and residential areas. The Boolean overlay method used criteria, such as stream order and fault proximity for binary classification, providing a comprehensive approach to site suitability assessment [29]. In a study by [30], they emphasize the importance of proper site selection for dams and water harvesting to combat water scarcity and enhance agricultural productivity. Critical factors include slope, soil type, vegetation, rainfall, and runoff capacity. Drone-assisted topographic analysis can optimize site selection, ensuring sustainable water management and agricultural resilience.

Abualhaija and Mohammad analyzed the Kufranja Dam in Jordan to address water shortages in an arid climate with limited freshwater resources. They concluded that the key factors for successful dam construction include geological surveys, hydrological features, and environmental impacts on agriculture and urban development [31].

Wang *et al*. highlight the importance of scientific dam location and construction for irrigation, flood control, and hydroelectric power. They discuss GIS/RS, Multi-Criteria Decision Making (MCDM), and machine learning as vital siting methods, emphasizing hydrology, geology, and socio-economic factors. They resulted in neglecting these considerations will risk environmental damage and dam failures [23]. Rather *et al*. examine the challenges of dam site selection in the Jhelum Basin, emphasizing that inadequate consideration of factors, such as landslide-prone areas and unstable soils can lead to dam failures. They stress the need to thoroughly evaluate topography, hydrology, geology, and socio-environmental factors. The study highlights that poorly located dams fail to manage floods effectively. The authors recommend adopting a multi-criteria analysis approach to address these issues to enhance site selection and prevent future failures [32].

In conclusion, various studies highlight the importance of selecting the proper site for small dams to ensure stability, effectiveness, and sustainable water management. Modern approaches integrate GIS, RS, hydrological modeling, and advanced decision-making methods, such as FAHP, ANFIS, WLC, and Boolean overlay. These methods assess runoff potential, slope, soil type, vegetation, proximity to communities and agricultural land, and the availability of quality fill materials. In addition, topographic analysis using drones has been proposed to optimize site selection. These researches underscore the necessity of addressing hydrological, geological, and socio-economic factors to mitigate challenges, such as water scarcity, population growth, climate change, and unstable soils. Case studies reveal that poorly selected sites risk dam failure, environmental damage, and ineffective flood management, emphasizing the need for comprehensive, multi-criteria analysis to enhance decision-making and improve water infrastructure resilience.

Numerous studies have been conducted in Iraq on dam site selection using different parameters [33]–[36]. For example, Al-Ansari *et al*. tested two areas (northwestern and northeastern parts of Iraq) for the feasibility of WH using small dams not more than 6 m in height. They identified suitable sites for small dam construction based on different parameters and applied the Watershed Modeling System and linear programming optimization techniques [37]. Another study to select optimal dam sites was conducted in the Deewana watershed (North of Iraq) using a combination of RS and GIS with multi-criteria decision analysis models. As a result, they identified (5.55%) and (21.81%) as highly suitable for constructing dams in the dam site selection maps and found that 11 proposed dam sites are ideal for dam construction [38].

3. GEOLOGY STUDY

Studying geology in dam design is essential for ensuring the structure's stability and safety by analyzing site conditions, foundation properties, and construction materials [39]. It involves geological mapping, geophysical surveys, and borehole sampling to evaluate rock and soil quality, permeability, and bearing capacity. Geological hazards, such as earthquakes, landslides, and karst features are assessed to mitigate risks. In addition, the availability and durability of local materials are tested for suitability in construction [40]. Tools, such as GeoStudio and GIS aid in seepage analysis, slope stability, and site mapping, ensuring a safe and efficient dam design tailored to the geological context [41].

Sissakian *et al*. highlighted the importance of geological investigations in dam construction, using the Mosul Dam to show the risks of inadequate assessments. Before site selection, they emphasized evaluating foundation geology, reservoir integrity, slope stability, and material availability. The process includes three steps: preliminary investigations for general insights, initial design studies for detailed data, and final design assessments for engineering needs. Key recommendations include geological mapping, drilling, and hydrogeological studies. Misinterpreting geological data, such as karstification and gypsum behavior, led to challenges at Mosul Dam, underscoring the need for thorough, expert-led evaluations to ensure dam safety [42].

Birhanu *et al*. evaluated the Upper Guder Dam slope stability in Central Ethiopia, addressing critical issues related to small dam construction, such as site preparation, material selection, spillway design, and costs. The results show that geological formations are susceptible to leakage and instability due to complex discontinuities and geological variances, particularly in the left abutment, which poses wedge failure risks. In contrast, increased pore water pressure compromises the right abutment's stability under saturated conditions. The study emphasized the importance of comprehensive geological assessments during the design and construction phases to prevent failures [43].

In summary, Geological studies are essential in dam design to ensure stability and safety by analyzing site conditions, foundation properties, and material suitability. These involve mapping, surveys, and sampling to assess hazards, such as landslides, earthquakes, and karst features. Tools, such as GeoStudio and GIS aid in seepage analysis and slope stability. Misinterpreted geological features have caused failures in past projects, highlighting the need for thorough, expert-led assessments. Comprehensive evaluations during design and construction address issues, such as material selection, spillway design, and abutment stability, ensuring safe and efficient dam construction.

4. HYDROLOGICAL STUDY

The hydrological study is essential for estimating peak floods with different return periods and average annual runoff that reaches the dam site to fill the reservoir. Moreover, assessing the sediment volume is considered in the hydrologic study [44]–[46]. Hydrological modeling tools, such as HEC-HMS and HEC-RAS, are increasingly used to predict peak discharges, assess flood risks, and evaluate dams' hydraulic performance. These tools help engineers determine the optimal size and structure of a dam to accommodate anticipated flood events while minimizing the risk of failure [47], [48].

Othman *et al*. applied a MCDM approach to assess dam sites, incorporating factors, such as soil type, elevation, precipitation, and proximity to faults. They highlighted the need for thorough geological and hydrological surveys, as past infrastructure suffered from inadequate evaluations [49].

Thieme *et al*. [50] highlight the importance of considering ecological impacts and hydrological changes during dam planning and construction. They note a rise in protected areas being downgraded or removed due to dam construction. They recommend avoiding dam construction near protected areas and removing problematic dams where possible. The paper calls for better alignment between development goals and ecological conservation to ensure functional freshwater ecosystems and urges policymakers to manage freshwater ecosystems responsibly and promote measures to restore rivers.

Hydrologic studies estimate peak floods, runoff, and sediment at dam sites, ensuring safe and efficient designs. Tools, such as HEC-HMS and HEC-RAS optimize dam performance and flood risk management. Surveys and multi-criteria approaches highlight the importance of hydrological considerations, urging avoidance of protected areas and addressing common dam failures, such as overtopping and erosion. Cascade systems require precise planning to manage peak flows and ensure effective flood mitigation.

5. DESIGN METHODOLOGIES

Small dams are vital in managing water resources, particularly in areas with irregular or limited rainfall. Historically, they have been indispensable for agriculture and ensuring food security. However, failures often occur due to poor design and construction deficiencies [51]. Once a dam site is preliminarily selected, conducting a detailed survey and developing area-volume-elevation curves are essential [18]. These are followed by adopting design methodologies tailored to site-specific conditions to ensure dam safety [52]. These methodologies involve analyzing geological, hydrological, and structural factors to optimize the dam type, foundation stability, and seepage control systems [43], [53].

Říha *et al*. [54] discussed small dam construction and operational dynamics, focusing on the cascade system along the Cižina River in the Czech Republic. Various construction methods were described, emphasizing the homogeneous nature of the dams built with clay and detailing their dimensions, materials, and emergency spillway configurations, which are critical for managing flood waters and preventing overtopping failures. Stability analysis is conducted by simulating breaching scenarios, considering overtopping and piping as potential failure modes. Seepage analysis was also critical, highlighting the vulnerability of small dams to erosion due to internal seepage pressures. The article cited that the most common causes of failure stem from overtopping and internal erosion, which is further complicated by insufficient spillway capacity compared to incoming floods.

The key aspects, according to numerous studies on dam design, can be included as follows:

1. Comprehensive Planning and Modeling: Thorough planning and advanced modeling are essential to address site-specific challenges, predict risks, and ensure dam safety and functionality [2], [55].
2. Material Selection and Construction Quality: Choosing appropriate materials, proper layering, and maintaining high construction standards are critical for ensuring the dam's stability and longevity [55]–[61]. Proper layering of materials, such as shell materials, gabions, cores, and filters is essential for ensuring stability and resisting seepage and erosion [55], [62], [63].
3. Dam Height and Reservoir Capacity: Determining the dam's height and reservoir capacity is crucial for meeting water storage needs while maintaining structural safety [56].
4. Foundation Evaluation: Assessing foundation stability [58], [64], [65], identifying potential seepage paths is essential for ensuring the dam's structural integrity and long-term performance [56], [66].
5. Structural Components and Hydraulic Management: Upstream and downstream slopes, spillways, and bottom outlets are vital in managing hydraulic pressures and preventing dam failures [57], [63], [64], [67].
6. Resilience Against Natural Hazards: Mitigating earthquake risks [2], [68] and extreme weather involves

robust spillway systems to manage water flow and prevent overtopping. Advanced tools, such as HEC-RAS and RS aid rainfall-runoff analysis, hydraulic modeling, and peak discharge predictions, enhancing resilience and minimizing community impact [55], [56].

7. Spillway and Bottom Outlet Design: The design of spillways and bottom outlets is crucial for managing water flow, preventing overtopping, and ensuring the safe release of excess water during high-flow events [55], [58], [60], [61], [63]. Computational fluid dynamics (CFD) techniques refine spillway design and performance evaluation [45]. While 3D finite element models analyze internal mechanics, including soil layering, material properties, and hydraulic interactions [69].
8. Physical Models and Numerical Simulations: Physical models and numerical simulations [70] combine experimental and numerical analyses to evaluate seepage characteristics and structural displacements under various loading conditions [62], [65]. Stability and seepage analysis is crucial for preventing failure risks associated with overtopping and piping, significant causes of dam failure [68]. Advanced tools, such as GeoStudio aid in seepage analysis, slope stability, and stress evaluation, incorporating factors, such as water pressure, seismic activity, and settlement risks [71]. The dam's composition, geometric design, and surrounding vegetation enhance stability by limiting erosion and improving resilience during peak precipitation events [69]. SEEP/W software analyzes hydraulic performance aspects, including clay core thickness, cutoff wall depth, uplift pressure, hydraulic gradient, and seepage discharge [72]. The clay cores and cutoff walls are essential in managing seepage, noting that their placement significantly affects hydraulic gradients and discharge rates [58]–[60], [73]. Finite element methods are used to analyze the dam's stability and seepage characteristics [74].
9. Sediment Estimation and Dam Sustainability: Sediment estimation in small dams is essential for assessing long-term functionality. Sedimentation reduces storage capacity, affecting water retention and flood control efficiency [75], [76]. Embaye *et al.* stressed the significance of stability analysis for small dams, focusing on slope assessments, spillway design, and bottom outlets to manage erosion, water flow, and sediment buildup. Challenges, such as sediment accumulation and weak water user associations were identified as key contributors to dam failures [77]. Abdullah *et al.* examined the status and opportunities for water harvesting in Iraq. They noted that sediment accumulation is a major challenge to dam functionality, especially in the Eastern Valleys, where high sediment loads reduce reservoir capacities. Strategies are employed to minimize soil erosion and address potential risks of failure caused by sediment accumulation or structural deficiencies [4].
10. Cost, Operation, and Management: The cost of dam construction and operation, along with regular monitoring and effective management, are crucial for ensuring long-term functionality and safety. Continuous assessment and maintenance help detect potential issues early, preventing costly failures and optimizing performance [2], [59], [66], [78].
11. Material Selection and Construction Techniques: The analysis emphasizes the importance of carefully selecting materials and construction techniques to prevent failure, including controlling moisture content in the core material and ensuring proper drainage to manage seepage. Appropriate design and execution of these elements are vital for the dam's long-term stability and performance in irrigation management [9]. The importance of drainage methods, such as toe or horizontal drains, to reduce seepage and improve dam resilience is emphasized in the study, with support provided for earth-fill dam design to ensure sustainability and safety [70]. Controlling the permeability ratio between the shell and core layers and using coarse-grained filters to manage seepage and prevent erosion are recommended [74].
12. Environmental Impact and Community Protection: Protecting communities and minimizing environmental impact are key considerations in dam design and management [2], [66], [74]. Kondolf and Yi [78] focus on dam renovation strategies to extend reservoirs' operational lifespan and mitigate adverse effects on river ecosystems. They discuss minor dam construction aspects, including structural retrofits, fish passage devices, modifications for improved environmental flow, and sustainable sediment management practices. The study advocates enhanced design and operation to meet ecological standards, concluding that proactive renovation efforts are crucial for enhancing reservoir sustainability and environmental functionality.

As a result, the design and management of small dams require comprehensive planning, material selection, and construction quality to ensure stability and longevity. Key aspects include site-specific evaluations, proper layering of materials, such as clay cores, and addressing seepage and erosion risks. Structural components, such as spillways, bottom outlets, and dam slopes are essential for managing hydraulic pressures and preventing failure. Advanced tools, such as HEC-RAS, CFD, and GeoStudio are used for modeling, stability analysis, and seepage management. Sediment accumulation is a significant challenge, reducing storage capacity and efficiency, especially in areas with high sediment loads. Regular monitoring and effective management help prevent costly failures, while sustainable practices, such as retrofitting and sediment flushing, can mitigate environmental impacts.

6. CLIMATE CHANGE AND RISK MANAGEMENT

Climate and socioeconomic changes continue to pose challenges to developing effective adaptation measures [79]. Climate change adds complexity to the design and management of small dams. Increased rainfall frequency and intensity and shifting temperature patterns can alter hydrological conditions in dam catchments, impacting runoff patterns and raising flood risks. Dam failure risk rises due to climate change, with more frequent and intense rainfall causing floods that exceed design capacities. Climate models predict that the return period of extreme flooding events will be reduced [80]. To mitigate these risks, it is recommended that dam design and operational protocols be updated, flood criteria be re-evaluated, regular inspections be conducted using updated hydrological models [81], and additional flood control infrastructure be constructed. Incorporating climate change into risk assessments ensures dams' long-term safety [82], protecting downstream communities, and enhancing water resource management [83].

7. RESULTS AND DISCUSSION

It is crucial to select proper dam sites for sustainable water resources management. New applied techniques include using GIS, RS, and hydrological modeling and integrating FAHP, ANFIS, and WLC. The main key factors confirmed by the studies are the runoff potential, rainfall depth, peak flood, topography slope, elevation, soil type and fault, LULC, and socio-economic aspects, such as proximity to communities, roads, and infrastructure. In contrast, neglecting these can lead to dam failure and environmental risk.

Focus is put on the geological studies that are crucial for dam design, ensuring stability through assessing site conditions, foundation, and material suitability. This includes geological mapping, evaluating rock and soil samples, testing foundation permeability and bearing capacity, and analyzing earthquake hazards. Seepage and slope stability analysis using GeoStudio are also essential. Case studies highlight failures due to misunderstanding geology in ensuring efficient dam construction. Effective reservoir management requires hydrological study assessments to estimate the peak floods, average annual runoff, and sediment volume at dam outlets; tools, such as HEC-HMS and HEC-RAS assist in assessing these parameters. MCDM approaches help to integrate hydrological and geological site selection factors. In addition, ecological considerations highlight the need not to use protected areas. Proper hydrological assessments and environmental impact mitigation ensure efficient dam performance.

The effectiveness of small dam design depends on good surveys and accurate design methodologies. Key design considerations include foundation stability, material selection, seepage control, and hydraulic management. Common overtopping failures highlight the need for robust spillway designs. Sediment estimation is critical for long-term functionality, while cost-effective construction and operational management ensure sustainability. Combining physical models and numerical simulations enhances stability assessments, improving small dams' resilience and efficiency. Climate change poses additional risks, altering hydrological patterns and increasing flood frequency, which should be considered in dam design and management.

8. CONCLUSIONS

Small dams are increasingly recognized as crucial for water resource management, especially in areas facing water scarcity and unpredictable climate conditions. While these dams offer a cost-effective solution, they present challenges, mainly when constructed without proper engineering practices. Such dams' stability, safety, and long-term functionality are key concerns, mostly when built by farmers without professional input. Despite these challenges, small dams remain essential in rural areas, providing vital services, such as irrigation, groundwater recharge, and flood control.

Research into small dam construction and performance highlights the importance of proper site selection, geological studies, and hydrological assessments to ensure these structures' safety and stability. Modern methods, including GIS, RS, and hydrological modeling, significantly improve site selection and dam design, aiding in more informed decision-making and reducing risks from poor construction practices. MCDM approaches, which assess hydrological, geological, and socio-economic factors, ensure these dams are resilient to climate change, water scarcity, and population pressures.

Geological studies are crucial for understanding site conditions, material suitability, and potential hazards, such as landslides or earthquakes. Tools, such as GeoStudio and GIS help engineers assess the seepage, slope stability, and material properties, thereby minimizing the risk of dam failure. Hydrological studies, including flood peak runoff and sediment volume estimations, guide the design of dams that can withstand extreme weather events and operate safely over time.

Comprehensive planning, material selection, structural analysis, and resilience strategies are key to effective dam design. Advanced tools, such as HEC-HMS, HEC-RAS, and CFD improve dam safety by addressing overtopping, internal erosion, and seismic risks. Proper design of spillways, bottom outlets, and other structural components is critical for preventing failures, while numerical simulations and physical models offer insights into dam behavior under varying conditions.

Adopting modern site selection techniques, conducting thorough geological and hydrological assessments, adhering to engineering standards, and ensuring regular maintenance and inspections are essential for improving the safety and longevity of small dams. Ultimately, small dams' success hinges on careful planning, proper construction, and continuous monitoring, while incorporating climate change risks into design and management practices ensures their resilience in the face of evolving challenges.

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