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A review on significance and failure causes of small-scale irrigation dams in arid and semi-arid lands

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ABSTRACT

Water scarcity is increasingly becoming a significant challenge in arid and semi-arid lands. In these areas, small dams and reservoirs are important in providing water resources, supporting agricultural activities, and contributing to sustainable and resilient rural communities as they require an affordable investment. However, their frequent failures pose significant challenges to sustainable water management and agricultural development in these regions. This review study was developed based on the review of many international standards and guidelines from published studies in scientific journals in addition to information from practitioners. We examined the significance and causes of the failure of small dams and reservoirs; and discussed design criteria and considerations involved in their construction. The outcomes of this study offer valuable insights into the significance of small-scale irrigation dams and shed light on the multifaceted causes of their failure. A holistic approach to address the challenges identified is required. Integrating engineering solutions such as improving design, and regular maintenance, with sustainable land management are crucial for optimising the small dams and ensuring that they adequately serve the needs of the community. The causes of failure were found to be multifaceted encompassing factors such as poor construction and maintenance practices and inadequate design considerations. Finally, this review highlighted the key elements in assessing structural conditions critical to the functionality and sustainability of small dams and reservoirs.

Keywords: Arid, Design, semi-arid lands, Small Earthen Dams, Structural Conditions

1 Introduction

Water is basic for life, an absolute need for all human activities and animals. Population growth exacerbated by climate change drives an increase in public demand for water for various purposes. Thus, water availability is one of the greatest human concerns. However, water scarcity poses significant challenges and creates obstacles to crucial activities in arid and semi-arid lands (ASAL) and regions where it causes obstacles to irrigation and cultivation, cattle raising and people's survival [1, 2]. Moreover, rainfed agricultural activities in arid and semi-arid areas are particularly vulnerable to drought due to the unpredictable nature of rainfall in these regions. The development of water harvesting techniques like the construction of small dams and reservoirs are among the promising solutions that humans use in addressing water scarcity for common use [3]. Dams have aided human development by providing reliable sources of water, irrigation, income, and other vital advantages [4]. A dam is a hydraulic construction made of relatively impermeable substances that are built across a waterway to create a reservoir on its upstream side for impounding water for multiple purposes [5]. Additionally, many academics, such as [1, 4–7], defined a dam as a barrier placed across a river or stream that allows the water to be held back or impounded, delivering water for farming and drinking, controlling flooding, and generating power. Dams are artificial structures that catch water and modify both the amount and timing of the water that flows downstream [7].

The usefulness of small dam construction can be estimated beyond water availability to the contribution of land sustainability by controlling floods and reducing soil erosion leading to gully caused by high runoff [8]. This emphasises that if there are no efforts to control water in the rainy season, it can cause erosion and flooding, while in the dry season, it will be dry and difficult to attain water sources [6, 9]. Hence, small-scale irrigation dams play an important role in storing water during periods of high rainfall, which can be utilised for multi purposes like irrigation, domestic and livestock during the dry season. In addition to water storage, a study conducted in Canada by [7], stated that small dams showed other positive effects in the reduction of floods in agricultural watersheds, and significantly reduced sediment, nitrogen and phosphorus loading to streams.

However, cases of failure and collapse of small dams have been reported to be constantly increasing and this situation led to the failure in meeting their expectations. It has been reported that dam failures are primarily related to leakage, piping and overtopping due to heavy seasonal rainfalls and poor design [5]. The design and assessment of engineering conditions of dams involve various considerations to ensure their safety, efficiency and sustainability. Moreover, some factors like catchment area, rainfall patterns and water demand are analysed to estimate the required storage capacity.

Furthermore, the selection of suitability site for dams construction depends on different factors [10]. Therefore, these infrastructure must be located in suitable locations to successfully meet the demands [6]. Most importantly, the design process of small-scale irrigation dams begins with a preliminary site assessment to identify suitable locations with optimal water collection, topography and soil conditions.

This research review focussed on small earthen dams with more emphasis on significance, design principles, structural, engineering conditions, and overall dam system striving for an assessment to create safe and efficient water storage facilities that support agricultural activities and contribute to rural water availability.

2. Importance and Design Criteria of Small-Scale Irrigation Dams

2.1. Importance of Small-Scale Irrigation Dams

Small dams offer a lifeline to rural communities [11] particularly in many arid and semi-arid areas, where temperatures and evaporation are often at peak in the dry season and unpredictable rainfall parts. Agriculture and pre-rainy season establishment of crops cannot be undertaken without large quantities of water. The development of small dams has the potential for water scarcity and flood mitigation by enhancing rainfall water harvesting practices for sustainable water management in these areas.

Small earthen dams have played a significant role in addressing water scarcity and supporting rural livelihoods in regions with limited access to water sources [9–11]. Furthermore, small-scale irrigation dams contribute to improved water availability, increased agricultural activities [14], water scarcity mitigation, empowerment of smallholder farmers, and create sustainable awareness in water management and climate change adaptation [15]. By creating alternatives to water sources and reducing dependence on rainfed agriculture under erratic rainfall conditions, small-scale irrigation dams help farmers to adapt and withstand changing climate conditions [14, 15], hence enhancing the resilience of local communities. Small dams facilitate the efficient utilisation of water resources, the stored water can ensure optimal water use and reduce the environmental impacts downstream [17], since their set-up is to capture and store water during periods of excess, preventing it to be wasted or causing floods. In addition, earthen dams present advantages for rural communities due to their proximity and quick responses of water availability for multi-usages, and lower construction cost than other types of dams, such as concrete dams. Regarding small-scale irrigation dams, earth-fill dams are the most common type of dam because their construction involves the use of materials from required excavations and the use of locally available materials requiring a minimum of processing.

Based on positive implications, small irrigation dams serve as multipurpose infrastructure providing benefits in addition to agriculture, they can support drinking water supply, livestock and watering and recreational activities. With regards to the cost-benefit, the financial benefits from the cultivation of land in many parts of the world are rarely large enough to allow for expensive, technologically advanced concrete structures to be built for impounding water. Therefore, according to Food and Agricultural Organization Manual on Small Earth Dams [18], the alternative is normally an earth dam or simple weir to alleviate the stressful water demands with available means. In response to the population growth and the drastic effects of climate change, small dams should be constructed coinciding with rising demands for water. Embankment dams are therefore readily recognized they have many advantages over equivalent concrete structures since they are most appropriate for farm or other rural situations [19]. As climate change poses continuous challenges to agriculture, small irrigation dams offer adaptive measures by providing a buffer against climate variability. However, the irrigation demands from a dam must be linked to the yield of the catchment contributing to the reservoir inflow and further downstream water users. Engineering conditions of small-scale irrigation earthen dams are crucial for being able to provide reliable water supplies, supporting agricultural activities, contributing to risk management and empowering communities.

2.2. Composition of Embankment Dams

Embankment dams are classified into two (2) main categories based on the type of soil mainly used as construction materials such as earthfill dams and rockfill dams [19]. The selection of a particular type depends on the availability of construction materials [20], project requirements and cost considerations. An earth fill dam is a type of embankment dam constructed using compacted earth or soil. The dam's core is made of impermeable material such as clay or clay silt while the outer shell consists of coarser materials like rock, gravel or sand. Rockfill dams are constructed primarily using rockfill materials. The central core is made of impermeable materials similar to earth dams but the out shell is composed of rocks and boulders which provide stability and erosion resistance. Figure 1 presents the types of embankment dams. A homogeneous earthfill dam is constructed entirely using compacted earth or soil without any distinct zoning materials [21]. However, a rock-fill dam with a facing is constructed with an inner impermeable core usually made of compacted earth while the upstream face is covered with a layer of concrete to provide a water-tight barrier [21].

Constructing a dam is a challenging process [22] that requires taking into account a number of factors in order to ensure the structure's robustness, safety, and environmental sustainability.

Through the entire process and stages as illustrated in Figure 2, interdisciplinary collaboration among different stakeholders, such as engineers, geologists, environmental scientists and regulating agencies [18] is very important to successful dam construction. Figure 2 presents a series of essential stages and considerations involved in dam construction to ensure the safety, stability, and long-term functionality of the structure that are crucial such as: (i) site selection; (ii) design engineering; (iii) site preparation; (iv) core construction;(v) Embankment and spillway construction; (vi) rigorous testing and inspections; and (vii) maintenance. In addition to technical aspect, local communities' involvement in planning and construction process is key asset for acceptance and sustainable dam projects [23].

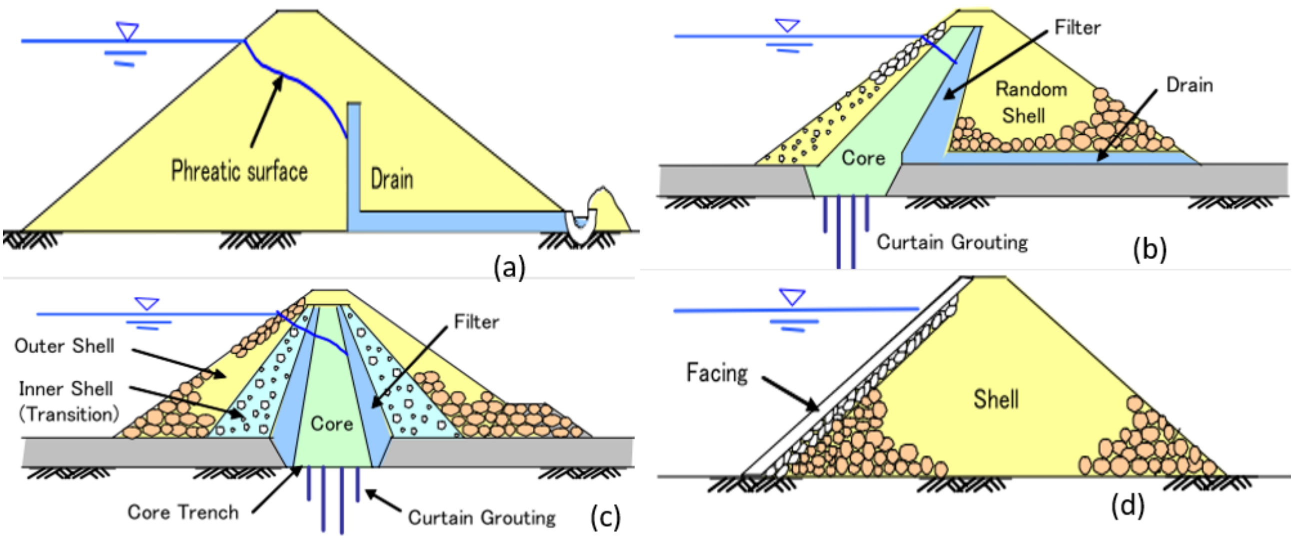

Figure 1. Earth and Rockfill Dams with (a) Homogeneous Earth dam; (b) Rockfill Dam with a Centrally Located Core; (c) Rockfill Dam with an inclined Core; (d) Rockfill Dam with a Facing: Source [24]

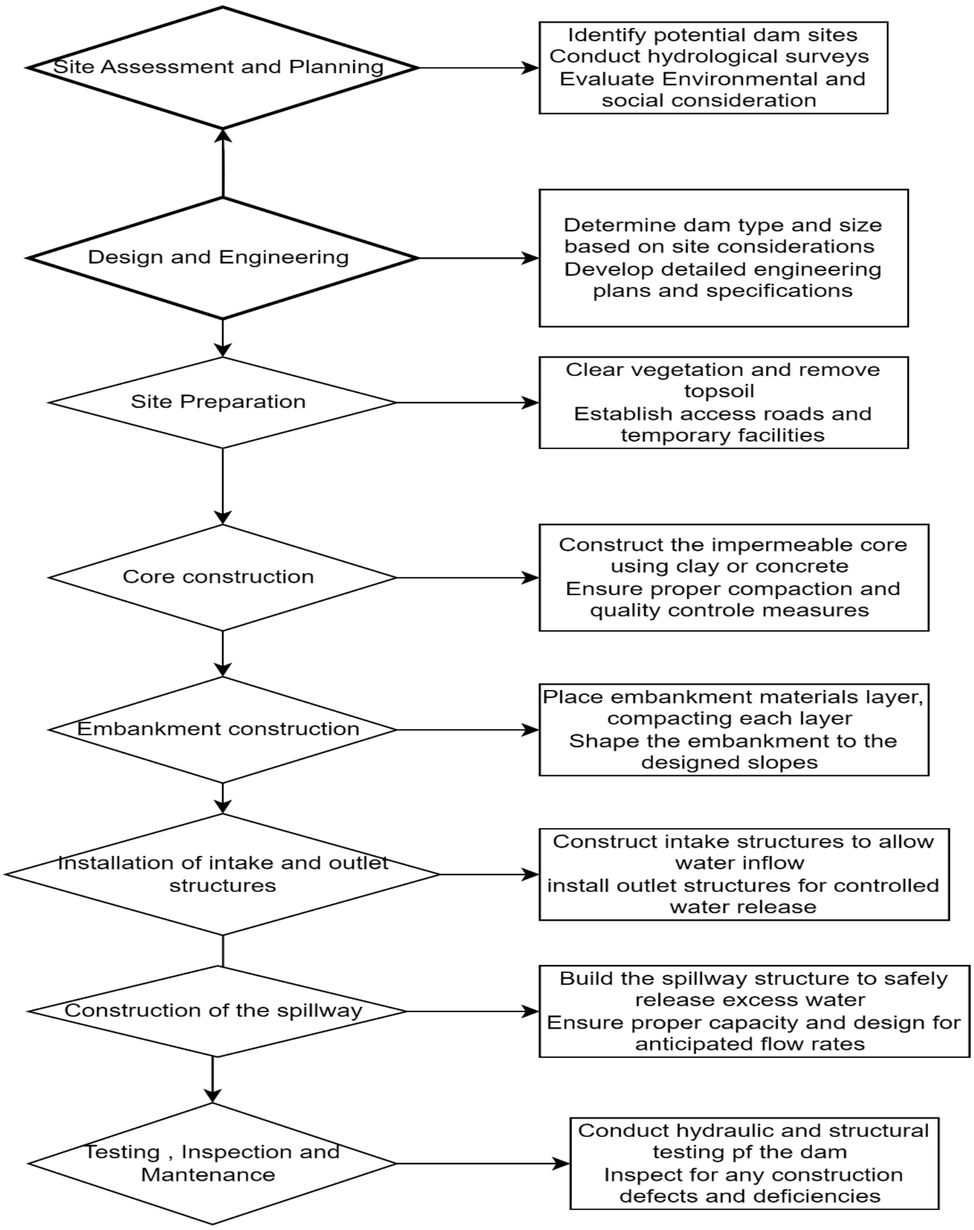

Figure 2. Indispensable stages and consideration for dam construction

2.3. Causes of Failure and Damages of Embankment Dams

Although there are numerous advantages of earthfill dams also known as embankment dams, are not without the potential for failure and damage [25]. Most catastrophic failures and malfunctioning of embankment dams pose threats to downstream communities [19]. Dam failure can have drastic effects including loss of life, property damage, disruption of water supply for different beneficiaries and environmental impacts as well. It is important to note that the causes of embankment dams can be occurred at different stages [26]. The study by [27] highlighted that major contributors to earth dam failure are overtopping, piping and structural failure. Figure 3 represents some common causes of failures and damages of embankment dams.

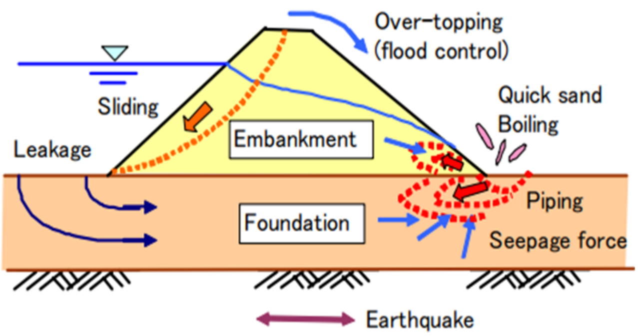

Figure 3. Diagrammatic representation of causes of dam failure: Source [24]

As presented in Figure 3, factors leading to embankment dam failures include:

(i) Overtopping: It occurs when the water level in the reservoir exceeds the height of the dam crest resulting in water flowing over the top of the dam;

(ii) Seepage and piping: Seepage refers to the flow of water through the embankment or foundation [28] while piping is a more severe form of seepage, piping occurs when the seepage water erodes and channels through the dam, creating internal passages that can read to the collapse of the dam;

(iii) Foundation failure: The foundation plays a crucial role in the dam's stability. If the foundation is weak or prone to settlement, it can cause differential movement in the dam, leading to cracks, deformations and lead potential failure,

(iv) Construction and design deficiencies: Poor construction practices and design flows can result in failures and damage to embankment dams. Inadequate compaction, improper placement of materials, insufficient or poorly designed drainage systems, spillways or errors in structural analysis can compromise the overall integrity of the dam,

(v) Natural disasters: Embankment dams are susceptible to damage from natural disasters such as earthquakes, floods and landslides,

(vi) Lack of Maintenance: Over time, embankment dams may experience deterioration due to ageing and lack of proper maintenance.

It is worth noting that all damages from embankment dam failures are classified into three (3) types such as seepage failure, sliding and overflow [26]. However, even though embankment dams should not be built to withstand the erosive effects of water flowing over the crest, studies carried out by [18, 21] showed that insufficient estimation of the amount of flooding has often led to the decisive defeat of embankment dams. The preponderance of catastrophic earthen dam failures is triggered by reservoir water overflowing due to flooding or a loss of freeboard [30]. Overtopping has frequently caused embankments to fail due to insufficient spillway capacity, or inadequate water volume prediction of the volume of water [2].

2.4. Design Principles and Construction Considerations of Earthen Dam

Although small earthen dams do not require the building of intricate foundations like concrete dams, they must fulfil some standards. The construction and management of small-scale irrigation earthen dams require careful engineering considerations. For instance, the engineering design of small-scale irrigation dams encompasses several key elements. These include the dam's height, length, and cross-section shape, which are determined based on the volume of water and the site's hydrological characteristics [5]. To achieve minimum cost, the dam must be designed for maximum use of the most economical materials available, including materials excavated for its foundations and for appurtenant structures. Mostly, there are three (3) main steps in implementing a dam project as presented in Figure 4.

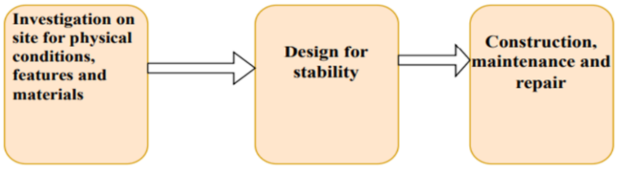

Figure 4. Implementation steps for the dam project: Source[31]

The design and construction of an earthen dam should adhere to engineering standards to ensure safety and successful construction. All phases of the construction and operation of the reservoir must verify safety and stability [21]. To accomplish these, the following criteria must be followed:

(i) The embankment, foundation, abutments and reservoir must be stable and must not develop unacceptable deformations under all loading and stress conditions,

(ii) Seepage flows through the embankment, and the foundation must be controlled to prevent excessive uplift pressures: piping, instability, sloughing, removal of materials by solution or erosion of material into cracks, joints or cavities. Also, the amount of water lost through seepage must be controlled to keep planned project functions

(iii) The reservoir rim must be stable under all operating conditions to prevent the triggering of landside into the reservoir that could cause a large wave to overtop the dam.

(iv) The embankment must be safe against the overtopping or encroachment of the freeboard during the occurrence of the inflow design flood (IDF) by providing sufficient spillway and outlet capacity. Designing an earth dam embankment primarily involves determining the cross section that when constructed with the available materials will fulfil its required functions with adequate safety at minimum cost.

(v) Freeboard must be sufficient to prevent overtopping by waves. It serves as a protective measure to maintain dam stability and prevent potential damage that could be caused by wave action during storm events.

(vi) The upstream slope must be protected against destructive wave erosion and the crest and downstream slop must be protected against wind and erosion. The upstream slope protection should extend from the crest to a safe distance below the minimum water level [2]. The experience has shown that in most cases dumped riprap furnishes the best upstream slope at the lowest cost.

2.5. Hydrological Analysis and Dam Sizing

Relevant hydrological data such as historical precipitation, up-catchment physical features influencing runoff, and stream flow patterns are essential for understanding the hydrological characteristics of the catchment where the dam will be constructed. This was confirmed in the study conducted by [32] which proposed the simulation and optimization of a framework that can assist in sizing check dams for sustainable and effective watershed management. The hydrological analysis results, determine the required storage capacity of the dam to meet the desired objectives [33].

According to [34], the selection of a suitable area for dam construction could be done based on the steps outlined in the flow chart presented in Figure 5.

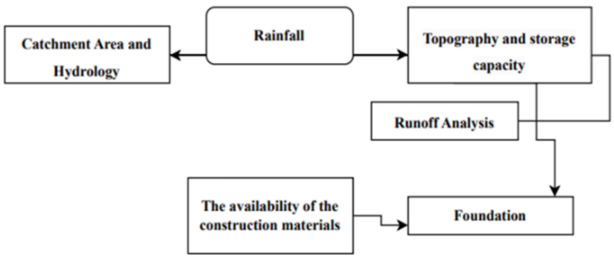

Figure 5. Key factors for dam construction. Source: [34]

Where:

i. Topography and storage capacity: Topographic maps are indispensable in the design and construction of a dam, for the economic feasibility of a storage project, the length of the farm dam embankment body must be as small as possible and for a given height it should store a maximum volume of water.

ii. Catchment area and Hydrology: This consists of the delineation of the boundaries of the catchment area that contributes water to the dam site. The catchment area upstream of the farm dam location should be sufficient catchment and it is expected that it will bring enough amount of water to fill the reservoir. To be sure about this factor, the hydrological characterization of the catchment area should be prepared.

iii. Runoff analysis: The calculation of the runoff generated by the catchment based on the rainfall data and the catchment characteristics like land use, and soil type slope, this analysis requires empirical methods to estimate the volume and timing of runoff.

iv. Foundation: Despite that small dams are not subject to appreciable post-construction settlement when saturated, little foundation preparation is required [4]. Information on the foundation is therefore essential for the design of all dams.

The essential requirements of a foundation for an earthen dam are that it provided stable support or the embankment under all conditions of saturation and loading. It is very important to find the soil permeability, the location of bedrock and to know whether the foundation is pervious or impervious. The availability of the construction materials relevant to the economic feasibility of the project needs to have suitable construction materials nearby.

2.6. Typical Evidence of Small Earthen Dams Implementations in Africa

The effect climate change is having on livelihoods and food security is of great concern to many nations, various African countries implemented small earthen dams to address water scarcity, improve irrigation and support agricultural development. In Ghana, high levels of poverty in the northern parts of the country are due to lower rainfall during its single rainy season [13]. As this part of the country is located in arid and semi-arid lands (ASAL), it faces challenges related to limited rainfall and water resources. Small earthen dam development improved Ghana's rural economy since the post-colonial period [11]. One Village-One Dam (1V1D) is an infrastructure development policy initiative implemented in 2017 by the government of Ghana targeting the northern regions of the country. The initiative intended to provide access to reliable water sources for agricultural purposes through the construction of small-scale irrigation dams in various villages. Despite the good perspectives to transform agricultural practices and improve livelihoods in the northern regions, the quality and effectiveness of some constructed dams did not meet expectations [35]. In Tanzania, Mlele Dam is an example of a small earthen dam project specifically designed for small-scale irrigation purposes.

Burkina Faso has been actively involved in the construction of earthen dams to address water scarcity issues through projects like the small dams program (Programme des Petits Barrages) to build and maintain small earthen dams across the country [16].

In Kenya, small earthen dams have been constructed in various regions to support irrigation and livestock watering where the National Irrigation Boards has been involved in implementation projects smallholder irrigation and value addition Project

(SIVAP) that includes the construction of small earthen dams [36].

In Malawi, despite the vast water resources, climate change, coupled with increasing population and urbanisation is contributing to increasing water scarcity, the country has implemented small earthen dam projects as part of its efforts to improve water availability and enhance agricultural productivity, through the Ministry of Agriculture, and water development to support irrigation schemes and promote food security [37].

In Nigeria, small earthen dams have been implemented to address water scarcity and improve agricultural practices through Small Earth Dams Programme (SEDP) initiated by Water Resources Institute [38]

Zimbabwe, the government along with organisations has implemented Smallholder Irrigation Rehabilitation and Development Projects (SIRDP) where small earthen dams projects were undertaken to enhance water resources management and support agricultural activities [39]

3. Criteria Describing Dams and Engineering Conditions

3.1 Classification Criteria of Dams

Dams may be classified into several different categories depending upon the purpose of the classification [40]. Some criteria, such as physical factors are taken into consideration in the selection of dam types such as geology, topography, and hydrology are essential requirements for planning for selecting dam types. However, other criteria are used to characterize dams from an engineering perspective [1] like the use of the hydraulic design or the materials of which they are constructed. Furthermore, during the 19th and 20th centuries, new technologies allowed the construction of much larger and more complicated structures to generate hydroelectricity, control floods, provide drinking water, support large-scale irrigation, and improve navigation [41]. Dams vary tremendously in size (height and width) and hence in their reservoir storage volume. Therefore, some dams may fall into multiple categories depending on their characteristics and intended functions. For example, the United States Army Corps of Engineers National Inventory of Dams[41] defines dams as large if they meet one of three criteria: (i) high hazards potential (e.g. likely loss of human life if dams fail), regardless of the dams absolute size; (ii) a low hazard potential but height exceeding about 7.6 metres (m) and storage exceeding 61,700 cubic meters (m^3) or, (iii) low hazard potential but storage exceeding 18,500 m^3. The International Commission on Large Dams (ICLD) classifies dams as large if their height exceeds 15 m. Dams' classification framework can be categorised based on purpose, construction materials, design and size.

3.2 Evaluation of Structural and Engineering Conditions of Dams

Regular evaluation of the structural and engineering conditions of small dams is imperative in identifying potential issues before they escalate into critical problems. Dams' engineering conditions can be evaluated based on various factors related to their design, construction, performance and safety. The checklist targets to qualitatively evaluate the structural and engineering constructions of embankment spillways and water intake facilities. Several criteria are used to characterize dams from an engineering perspective [42].

Some of the key steps and considerations for evaluating the engineering conditions of dams can be stated as:

(a) Review design document: The dam's intended design features and requirements can be understood through reviewing engineering drawings, calculations, and specifications.
(b) Site inspections: Perform thorough site inspections to assess the physical condition of the dam and its associated structures. This involves visually inspecting the dam, spillways, outlets, embankments, and appurtenant structures. Also, the same survey can be conducted to look for signs of erosion, seepage, settlement and other issues that can affect the dam's performance.
(c) Seepage analysis: Evaluate the seepage characteristics of the dam and its foundation, this includes the adequacy of the impervious core, filters, drainage systems and grouting.
(d) Structural integrity Assessment: This includes evaluating the stability of concrete, or masonry structures.
(e) Hydraulic Analysis: Perform hydraulic analysis to evaluate the dam's ability to handle inflows, outflows, and floods events.
(f) Safety assessment and scenarios: This includes assessing a comprehensive safety assessment of the dam considering possible failure modes and levels of risks downstream communities for emergency preparedness plans and measures to mitigate risks.
(g) Environmental considerations: Environmental impacts assessment of the dam and evaluate its regulatory requirement.

4. Conclusion

The review underscores the vital role of small dams and reservoirs in arid and semi-arid lands end emphasizes the importance of meticulous design, construction, operation, and maintenance practices. By comprehending the potential causes of failure and implementing appropriate engineering measures, that can offer alternative and reliable water sources. Investment in the appropriate construction of small dams could help address the increasing demand on livelihoods due to climate change, and rainfall variability population growth which are undermining wellbeing in developing countries, especially in arid and semi-arid areas. Despite being little investigated, small-scale irrigation dams frequently fail to meet their expected demands. The engineering conditions for small-scale irrigation earthen dams are crucial. Therefore, the safety and functionality improvement of small dams should have special attention regarding their implementations for ensuring long-term sustainability. In addition, hydrological characteristics and catchment delineation should be taken into consideration. This review paper presented the importance of small dams for the development of agricultural activity and water availability in rural with limited surface flows. A thorough assessment of structural conditions for small-scale irrigation earthen dams provided an insight foundation for failure risk reduction and sustainable water resources management.

Through a comprehensive evaluation of various factors, the overall condition performance of these structures' engineering conditions safety and stability were highlighted. Their strategic location and design are essential to optimize water storage and support livelihoods in these water-stressed environments. Therefore, further research should consider the catchment's physical characteristics related to runoff and suitable location for small earthen dams including the model for the selection of suitable sites, and water storage capacity.

5. Authors' Contribution

Conceptualization, EU; methodology, EU; investigation, EU; writing original draft preparation EU; visualization, and editing, FKA and TAA; supervision, FKA. AAP; project administration and funding acquisition, FKA, TAA. All authors have read and agreed to publish the version of the manuscript

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