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Rubber Dams in Sustainable Water Resource Management: A Comprehensive Review of Applications, Benefits, and Future Directions

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ABSTRACT

Water scarcity and flooding are serious universal problems, which are aggravated by population growth, urbanization, and climate change, and which today impact over 2 billion people with a loss of economic value of about 100 billion dollars in 2020 alone. As inflatable hydraulic constructions constructed using reinforced materials, rubber dams have become an effective technology in controlling water flow and storage within rivers, lakes, and reservoirs. The analysis demonstrates that the proportion of the current literature in the analysis is that 76% of the literature is general design and that only 24% consider any case study, with a large percentage of literature originating in Asia being 78%. They are essential in flood management, irrigation, domestic and industrial water supply, and small-scale hydropower generation, and have proved to be efficient across the geographical setting, including Hong Kong and Bangladesh. The review lists the environmental advantages of rubber dams, such as flexibility to changing water levels and less ecological disturbance than traditional concrete dams, and major economic benefits of much cheaper (up to 50% less) construction and maintenance. Social benefits include, among others, improved irrigation to guarantee food security and leisure. Nevertheless, the technical issues, such as the erosion of materials and the short life span (usually around 20 years), environmental effects on aquatic ecosystems, and complicated regulations, are quite significant drawbacks. The research gaps in this paper are mainly the validation of the performance under different hydroclimatic conditions and reinforcement of the policy support.

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1. Introduction

Due to population growth, urbanization, and climate change, water scarcity is a real issue for 2 billion people worldwide [1, 2]. A watermark shortage for demands defines it. Thus, water is scarce and has to be shared between agricultural, industrial, and domestic uses. The Middle East and North Africa region stand to be the most affected, with some countries currently in acute deficit [3, 4]. On the other hand, the effects of flooding are severe and are further worsened by climate change, which brings frequent and unusually extreme weather events [5]. This calamity is caused by several factors, including precipitation, rainfall, snow melting, and rising seawater levels that affect structures and productivity. The flood affected approximately 50 million in 2020 and resulted in losses of about $100 billion, respectively [6]. Table 1 shows the comparative overview of water challenges.

Table 1. Comparative overview of water challenges.

Challenge	Affected Population	Key Regions	Economic Impact
Water Scarcity	2 billion	Middle East, North Africa	High (varies by region)
Flooding	50 billion	Southeast Asia, Africa	$100 billion (2020)

Accordingly, sustainable hydrology is needed for global water problems, especially in areas with high water stress and climate change effects [7]. Sustainable hydrology is concerned with the rational utilization of water for the present requirements and future utilizations without causing any unpleasant consequences, which is also applicable to the reasonable storage and use of groundwater precipitate, especially in deserted areas [8]. Moreover, contributing to hydrological observation systems improves the knowledge of water supply availability and variability, as well as emerging changes related to climate impacts when designing the future demand for water supply [9].

Healthy rivers are imperative in sustaining ecosystem services, such as the regulation of floods and support of species, which are vital in the welfare of both the humans and the natural environment [10]. This significance is especially high in such areas as North Africa, where the uneven hydrological processes and the change of climate have further exacerbated the necessity of eco-friendly approaches to water management [11]. Rubber dams, which are regarded as one of the most effective modern water management tools, play a crucial role in the hydrological regulation at a global level [12]. These are reinforced rubber structures that can be inflated or deflated and used to regulate the flow and level of water in rivers, lakes, and reservoirs [13]. Unlike the standard concrete or earthen dams, the rubber dams have their own flexibility, as they can be adjusted to environmental standards, which is a highly valued characteristic in the contemporary dam construction [14]. Their main role is the fact they may inflate and deflate, known to manage the height and storage capacity dynamically depending on the amount of water in a river or reservoir [15]. This aspect is especially useful during heavy rainy seasons when unnecessary water may be stored to avoid floods. Rubber dams also offer good stock of water in seasonal rainfall areas when the rainfall fluctuates and no precipitation occurs during the dry seasons [16]. Riverbanks are normally fitted with rubber dams or built into the dams. When a pump moves water or air into an internal dam, the dam increases in height, forming a wall that retains water above [17]. This flexibility does not only improve flood control but also ensures water supply in areas that experience drought, which successfully addresses the problem of water shortage associated with climatic changes. Besides the advantages in their operations, rubber dams are also inexpensive and therefore do not need much capital investment like the traditional dams, and yet they are equally efficient [18]. They can be used in place of building conventional dams that cannot be operational in certain regions because of geographical factors; their construction is environmentally friendly and therefore minimizes the ecological disturbance [19]. Rubber dams, therefore, appear to be a critical option in water management of the present, as they will provide flexibility, save money, and offer environmental advantages. Their use in locations where hydrological conditions are variable illustrates their use as an important infrastructure for sustainable development amid climatic change [20].

The main principle of the rubber dams is a strong construction attached to the riverbank or the structure of the dam [17]. When pumping water or air in an interior bladder creates a rise in the dam, creating a boundary that contains water at the upstream side [18]. Particularly, the given design encourages and increases recreational experiences in the surrounding areas and enriches the fishing and boating experience in the vicinity [19]. Moreover, rubber dams are in most cases inflatable, making them cheaper to construct than the standard traditional dam, not to mention that they are easier to erect, particularly in regions where construction of the traditional dam would be unaffordable or would be too disruptive to the ecosystem [20]. Besides water control, rubber dams are also important in an extended way and could also enhance the quality of water by reducing erosion and sedimentation of water flowing down the river as well as leading to healthier watersheds [21]. Moreover, rubber dams are also useful in irrigation in the agricultural sector, as they provide water even in the case when the situation is dry everywhere. This factor is increasingly significant because of the increasing demand for agricultural products in the world, particularly in the developing world, where water shortages as a result of climate change are common [22]. This is to say that rubber dams are fully endorsed types of infrastructures used in the management of floods as well as for irrigation purposes and as part of continued ecological programs [23].

Rubber dams have also been commonly implemented in the world. These structures have been adopted in many countries; predominantly rubber dams are extensively used in the United States, Canada, and many countries in Europe and Asia, where the effectiveness of this technique is improved by the higher level of monitoring technologies, which allow real-time control over water data [24]. These systems exploit automated controls to maximize the flow control of water, adapt rapidly to the variability of rainfall, and protect other zones from flooding, as is emphasized in AlKhafaji et al. [2023] [25]. Through the combination of the automation of control with the rubber dams, the operators may guarantee accurate water management and responsiveness to the dynamic hydrology, which proves that the rubber dams may be used to cope with the water issues present in modern society. Such an integration of technology with the infrastructure highlights the significance of rubber dams as the key instruments in the reduction of the effects of climate variability. In addition to flood control and water retention, they are compliant with wider water resource management objectives addressing such problems as urban river pollution, eutrophication, and dam construction in the context of sustainability. The network of benefits that the rubber dams offer is also noted in Fig. 1, which connects it with some of the major subjects like the management of chemical pollution and the ecological balance of the river system and the urban landscape. Overcoming these environmental issues, rubber dams take center stage within the sustainable solutions, which are flexible, economically efficient, and environmentally friendly ways to manage water sources in various environments [26].

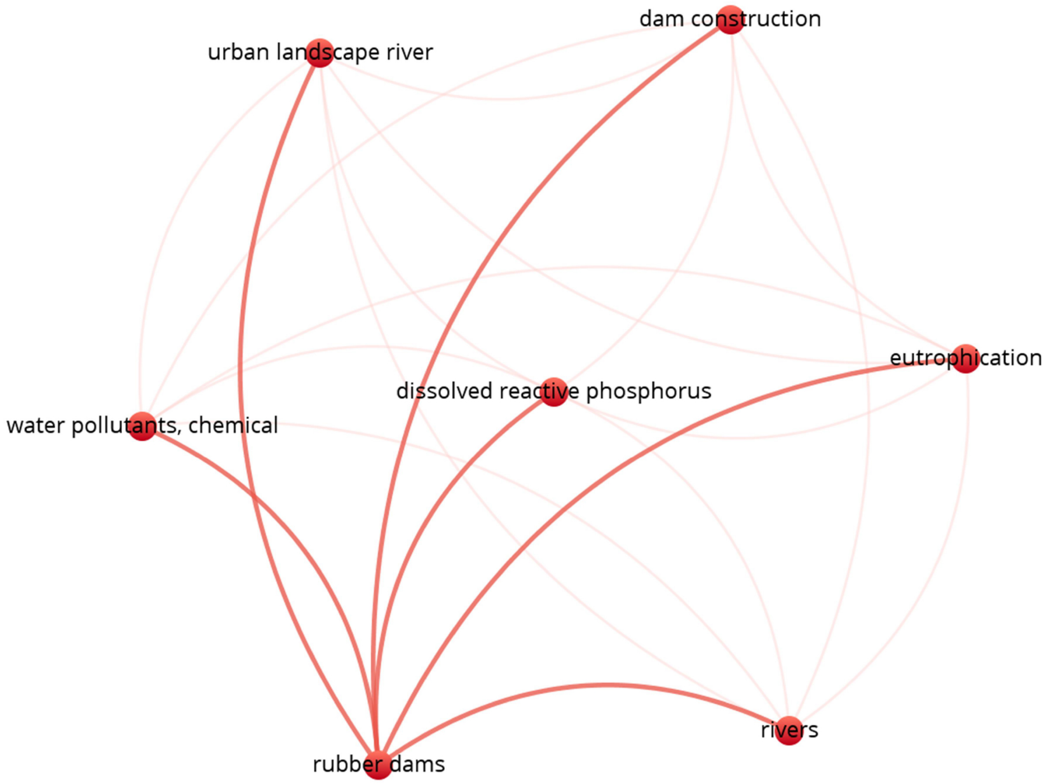

Fig. 1. Role of rubber dams in the water resource management.

As pollution is continuously changing, weather conditions are acute, the population is growing with its further concentration in relatively small areas, and the use of water resources is excessive, the rubber dam provides an opportunity for reasonable water consumption. Its use is also in response to the urgent necessities of contemporary work in regions that are affected by water, and it is in line with the environmental issues and goals. These characteristics boost the level of quantity control that is introduced, thereby adding to the balance of water resources that are fundamental in the development of sustainability. The factors of sustainable water management are displayed in Fig. 2. Although the usage of rubber dams in water management has been on the rise, there exist numerous gaps in understanding their effectiveness in diverse hydroclimatic conditions, ecological effects, and integration of advanced technology in improved operation [26].

Despite there having been increased global interest in rubber dams as an adaptable instrument of water management, the literature available does not give a definitive synthesis that simultaneously considers the environmental, economic and social aspects of the tool in various applications. Earlier reviews have been mainly piecemeal, claiming to address single, technical details or case studies without giving a comprehensive picture with regard to their advantages and weaknesses in the overall management of sustainable water resources. To address this glaring gap, this paper will establish a state-of-the-art review, which will be a synthesis of findings of peer-reviewed research, case studies, and technical reports published during the previous two decades. The method was a systematic search of scientific databases (e.g., Scopus, Web of Science, and Google Scholar) with the keywords of inflatable dams, rubber dams, flood control and sustainable water management. The

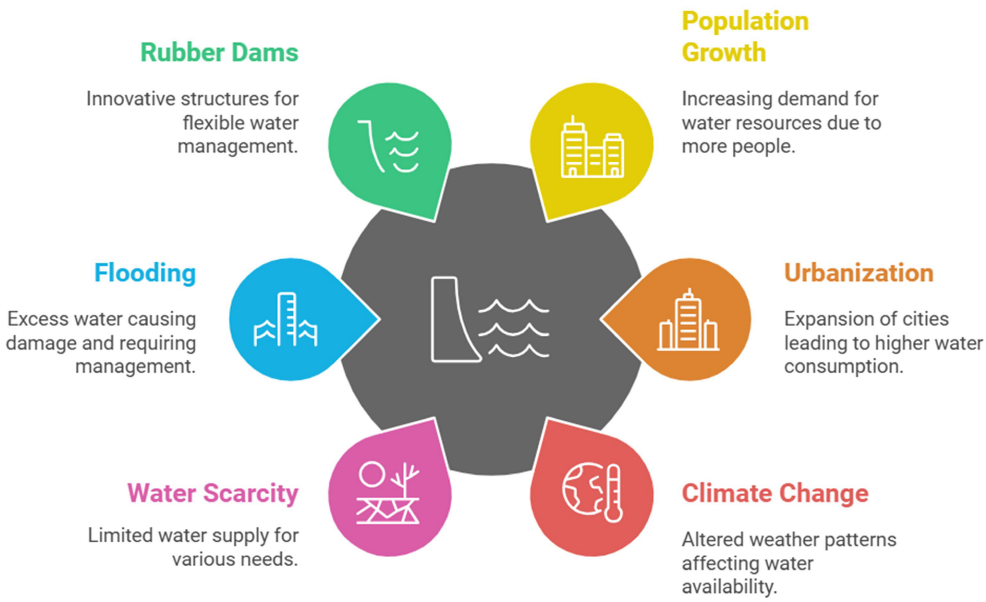

Fig. 2. Factors contributing to sustainable water management.

obtained literature was subsequently thematically analyzed to identify the main trends, summarize the results on multi-faceted benefits, outline the undying issues, and conduct a high-order statistical examination on the distribution and emphasis of research. In this way, this review can not only give a consolidated body of knowledge but also give a clear roadmap on how future research and policy development can be made to reap the maximum potential of rubber dam technology.

2. Overview of rubber dams

2.1. Definition and characteristics

Rubber dams are hydraulic inflatable structures that can be applied to transmit water, flood control, and irrigation. They are made in a way that they can be deflated or inflated depending on the water levels and the requirements in terms of operations and therefore they are versatile in handling water resources. Hydraulic rubber dams have the following characteristics:

2.1.1. Construction

These rubber dams are usually reinforced rubber material and they may be able to resist hydraulic pressure. They may be built at other locations such as rivers and lakes and are accepted because of the low construction expenses compared to concrete dams [27]. These dams are stronger at higher air pressure; therefore, high air pressure of 0.5 to 1.5 kPa can increase the resistance of these dams to floods [28]. Such flexibility is not available in the traditional dams, which are inflexible.

2.1.2. Operation

The working principle of operation of rubber dams is to fill up the structure with water or air and raise the height to prevent the flowing of water [29]. Due to their ability to be modified here and there, they come in handy when it comes to managing floods, as well as in irrigation [30].

2.1.3. Maintenance

Generally, maintenance of the rubber dams does not need much effort as opposed to the traditional dams. It however, needs some application in order to monitor aspects like wear out as a result of environmental influences like UV exposure and variations in temperatures [31]. Table 2 presents the main differences between rubber dams and traditional dams. Rubber dams are made of cloth coated with rubber and are also highly flexible and use inflatable (air or water) functions to allow the dynamism in adapting to water levels. They require fewer maintenance due to lower number of moving components and offer significantly lower capital and maintenance costs. Conversely, conventional dams, made of concrete or steel, are inflexible structures that depend on mechanical gates or spillways for functionality. These dams need increased maintenance to mitigate problems such as corrosion and mechanical deterioration and therefore are costlier to construct and sustain.

Table 2. Compares the rubber dams and traditional dams.

Feature	Rubber Dams	Traditional dams
Material	Rubber – coated fabric	Concrete or steel
Flexibility	Highly flexible	Rigid
Operation Mechanism	Inflatable (air/water)	Mechanical gates/ spillway
Maintenance	Low (fewer moving parts)	High (corrosion, mechanical issues
Cost	Lower capital and maintenance costs	Higher capital and maintenance costs

2.2. Design and engineering considerations

Rubber dams are created based on several structural principles, typical characteristics of site conditions, and hydrological factors affecting their design. Rubber dams, being flexible structures of air-filled inflatables, thus allow flexibility in handling water in different environments. The subsequent parts explain how the structural design was conceived and how the factors determining design decisions worked [32].

2.2.1. Structural design principles

Regarding structure setup, rubber dams are much different from the traditional types of dams [33]. Unlike concrete or earth fill dams, rubber dams exert pressure on the rubber membrane wall through the water column, do not require the support of gigantic concrete or earth pressure structures, and do not directly counter the huge water pressure the way the masses of concrete or earth fill structures do [34, 35]. It is also important that the insertion of the water pressure results in certain tensile stresses integrated into its design; the anchoring system must also provide the necessary force to withstand these stresses [35]. Besides materials, there are other qualities of the structural design, which concern the shape and mode of the dam construction (for example, cylindrical, inflatable, or various other forms) that depend on site conditions or the envisaged use of the dam [36]. There is also a consideration of the design of the anchoring system, as the structure must be anchored in its place despite the water levels and potential dynamic loads. It also utilizes safety factors for failure modes, membrane rupture, or anchor failure. The proper choice of materials is critical for providing the sustainable performance and durability of the Dam. The rubber membrane should offer adequate tensile strength, elongation, and behavior to environmental factors such as UV radiation and chemical attacks [37].

2.2.2. Factors influencing design choices

There are various aspects which are taken into account in designing rubber dams. Physical environment conditions of the location taking into consideration the topographical features of the rivers, the geology of the river bed, and the quality of the soil are among the most important issues to take into consideration [38]. The rate, depth and seasonal variation of water flow have significant impact on the design parameters [25]. The design aim of the dam also plays a significant role in considering other issues such as height, length, and the mode the dam is going to be, among others. To give an example, an engineering design of a flood management dam will not be the same as the engineering design of a water supply or water storage dam [39]. Additional considerations should also be done at this stage with connection to the environment, e.g., the impact on the wildlife in the water bodies or the surrounding environment in general [40]. The other characteristics are the nature of building materials at hand, project execution cost, and the legal aspects of the infrastructure project. Computer-aided models and simulations are nearly always needed to estimate the behavior of the dam to the loading conditions and Hancock [41]. Besides, proper maintenance and inclusion of inspection in the design is critical in the fulfillment of the overall functionality and safety of the dam during its service life [42]. The factors affecting the design of the rubber dam are indicated in Fig. 3.

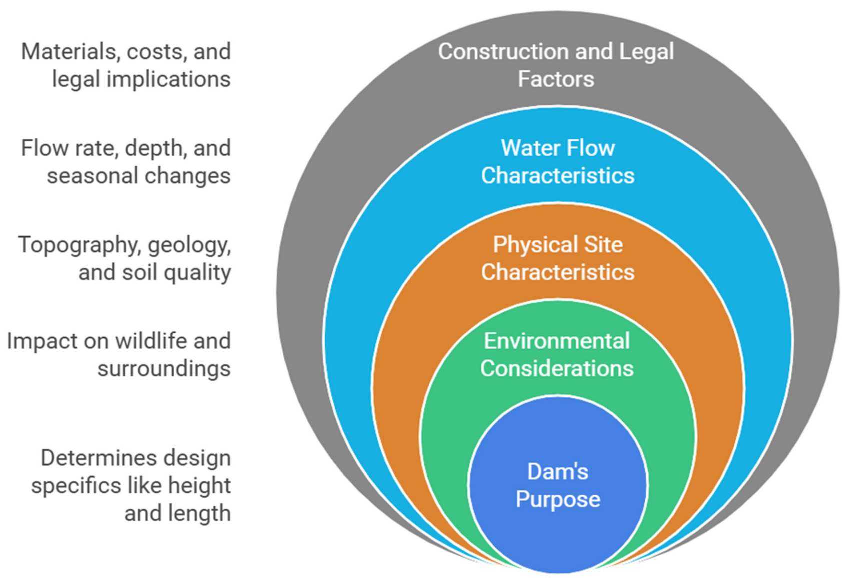

Fig. 3. Factors influencing rubber dam design.

This paper analyzes the advantages of rubber dams, focusing on their environmental, economic, and social benefits. The analysis draws upon various research papers to provide a comprehensive overview, highlighting both established findings and areas requiring further investigation.

2.3. Environmental benefits

2.3.1. Adaptability to varying water levels

The rubber dams can offer a huge benefit than to the environment primarily due to their flexibility in regard to change of level as pertains to water. Rubber dams adjust the water level by adjusting river flow compared to concrete dams where the level of water is comparatively constant [43]. Due to this fact, the natural hydrological regimes are preserved thereby scoring high in the index regarding no harm to aquatic life. The other benefit of the water management system to regulate the water level is that it assists in the sharing of water in some seasons to prevent shortage of water during drought or excessive supply of water during rainy season [44]. Therefore, flexibility is particularly necessary in the places where the rainy season is erratic and thus, water management becomes highly effective. An example of this is in Bangladesh whereby water shortage during dry seasons has been improved due to the use of low lift pumps, which improves through the use of rubber dams. This proves the flexibility of application of rubber dams in water storage and to be used in irrigation and practice of agricultural background [45].

2.3.2. Impact on aquatic ecosystems

The effects of rubber dams on the aquatic environment are a subject of contrasting outcomes in different research. Some studies show that the installation of rubber dams could generate some benefits, while there are works that point out drawbacks. In China, one study has noted higher diversity and abundance of plankton and some benthic organisms after integrating cascade rubber dams [46–48]. Nonetheless, the same study pointed out a decline in species diversity and a total shift of native fish species from streams by the exotic fish species. This indicates that although rubber dams have been said to improve other aspects of the aquatic environment, they cause drastic reductions in biodiversity and species equity. Managing water levels, which can be adjusted, will still impact aquatic life habitats. More scientific studies should be conducted to identify how rubber dams affect different water bodies and develop measures that could reduce the impacts of such dams on such resources. The effect on native fish populations should also be studied in detail because sourcing the native species with exotics alters an ecosystem dramatically [46].

2.4. Economic advantages

Among the significant benefits of economic rubber dams, greatly surpassing concrete or even earth-fill dams, cost-efficiency has been identified as the biggest. Lower construction costs could be attributed to lower design and construction complexity and, consequently, less consumption of material and workforce [33]. This makes them especially suitable for targeted developing countries with restrained budgets, where building huge hydropower stations could be economically unprofitable. This is complemented by the fact that the costs of maintaining rubber dams are cheaper than those of concrete dams. This is because rubber dams do not erode sediment or get destroyed easily by polls or other non-human physical forces. Since the maintenance required is lower, this is another way through which the economic aspect of the rubber dams is made economical to bring about an affordable water management and irrigation method. A comparative cost-to-benefit analysis with different types of dams in specific scenarios is needed to solidify the economic efficiency of rubber dams [49].

2.5. Social benefits

2.5.1. Impact on local communities

Local communities also gain a great deal from rubber dams in providing water to irrigate crops and develop recreational activities. Favorable measures in irrigation systems contribute to higher overall crop productivity and a corresponding increase in food self-sufficiency for the communities covered [50]. This often has an important implication for living standards and overall economic welfare. In addition, reservoirs behind rubber dams can also generate recreational activities like fishing and boating that are considerately auxiliary to the social/Leisure activity of the community. Conversely, the effects on locals may be the opposite if poorly controlled and formulated. For instance, dams built have been known to result in the relocation of people from their homes or loss of normal sources of income. Hence, social effects and engagements should also be considered cautiously so that rubber dam projects' social advantages are only beneficial [51].

2.5.2. Participation and acceptance by stakeholders

The studies show that stakeholders' acceptance is critical to influencing the rubber dam projects. Stakeholder participation is important in pre-planning, planning, implementing, and operating phases [52]. This ensures that the project meets the interests of the respective community and encourages the people to be responsible for sustaining the project. Stakeholder involvement in decision-making can balance gains in favor of all, reducing conflict. That notwithstanding, this approach entails low stakeholder involvement, which causes conflict and resistance, ultimately affecting the project outcome. The fact that the study on stakeholder involvement in water resources management and development supports the inclusion of stakeholders in dam projects is eloquent [53]. These approaches are necessary, especially when establishing rubber dams since the initiatives must become socially acceptable in the long run. Fig. 4 shows the summary of the advantages of rubber dams. Table 3 show the summary of Quantitative comparison of environmental, economic, and social aspects of rubber dams versus traditional concrete/steel dams.

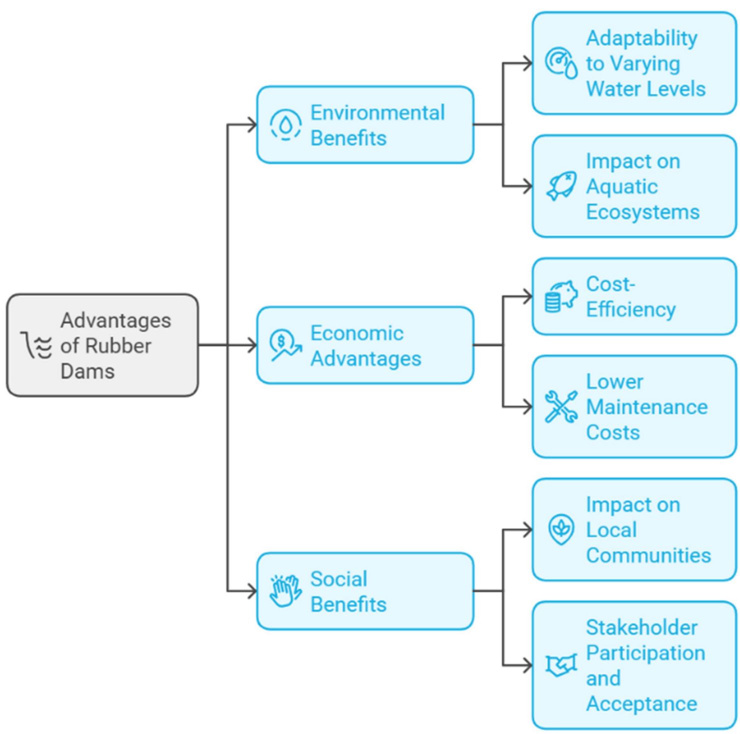

Fig. 4. Advantages of rubber dams.

Table 3. Quantitative comparison of environmental, economic, and social aspects of rubber dams versus traditional concrete/steel dams.

Aspect	Parameter	Rubber Dams	Traditional Dams (Concrete/Steel)	References
Economic	Capital Cost	~50% cheaper than conventional dams; 31% higher for imported vs. locally manufactured	Baseline (higher capital costs)	[4, 8]
	Construction Time	~5 months (1/10th of concrete dams)	~50 months (baseline)	[10]
	Maintenance Cost	Routine inspection: ~$3,600/year; Periodic (5-year): ~$137,500; Sediment dredging: ~$69,600/5-years	Higher (corrosion, mechanical issues, sediment management)	[6]
	Lifespan	20–40 years (typical 30+ years with proper maintenance)	50+ years (typical 50–100 years)	[2, 5, 10]
	Payback Period	~5 years (through hydropower revenues)	Longer payback period	[10]
Environmental	Adaptability	Adjustable to variable water levels; deflates during floods to prevent upstream flooding	Rigid; fixed water level; cannot adapt to extreme events	[1, 2]
	Ecological Impact	Minimal disruption when deflated; some obstruction remains; rubber material-water contact concerns	Complete barrier when in place; significant obstruction to fish migration and sediment transport	[2]
	Sediment Management	Deflation allows unobstructed flow, preventing sediment buildup	Requires mechanical dredging; traps sediment, altering river balance	[1, 2]
	Material Composition	Rubber-coated synthetic fiber; potential aging and degradation concerns	Concrete and steel; durable but high carbon footprint	[2]
Safety and Technical	Failure Modes	Vulnerable to punctures, vandalism, UV degradation, ice damage; can be equipped with pressure release valves	Vulnerable to earthquakes, seepage, structural fatigue; catastrophic failure potential	[1, 2, 5]
	Durability Issues	External damage causes 63.2% of repairs; no reported self-defects	Corrosion, concrete spalling, mechanical gate failure	[5]
	Operational Control	Slower inflation/deflation; difficult to maintain precise overflow depth	Rapid, precise control at any angle; can be completely lowered	[2]
Social	Installation Flexibility	Can be installed in remote locations; portable and relocatable	Requires heavy construction equipment; permanent structure	[1, 4]
	Community Benefits	Enables irrigation, small hydropower, recreational activities; supports rubber farmers	Large-scale water supply, hydropower, flood control; may require population relocation	[1, 4, 10]
	Aesthetics	Does not detract from natural landscape	Visually prominent; alters landscape significantly	[1]

3. Applications of rubber dams

3.1. Flood control

3.1.1. Case studies highlighting successful flood management

Research shows that rubber dams have proved useful in containing floods in different parts of the world. Being inflatable, they can be conveniently regulated to allow or refrain from water admission, thus minimizing floods [54]. For instance, twenty rubber dams in Hong Kong were established mainly for irrigation and function as flood control [55]. These are operated to swell and close the water flow during flood events and automatically open when the river discharge reaches a predetermined level, reducing flood impacts [55]. It also increases the frequency of silt and debris cleaning, improving flood control measures. The experience in Hong Kong shows that rubber dams can effectively regulate water levels, including in a relatively small river that may be subject to flood-genesis during intense precipitation [56]. Although the details of other successful flood management cases in using rubber dams appear to be absent in these documents, the experience from Hong Kong points to the evidence of the possibility of such use.

3.1.2. Mechanism of flood mitigation

The basic factor demonstrating the flood control ability of rubber dams is the fact that they are able to control the water flow dynamically. Once lifted, they become low level dams, and they store water to be used in irrigation or any other purpose. But still it is a fact that they can lower their buoyancy automatically as the water levels increase to a certain level as is needed to prevent floods. Such mechanical discharge removes this limitation on water flow and permits undesired water to pass through it and in this case, downstream storage is reduced. This type of operation is better than the traditional fixed-structure ones because they are not able to cope with the changes of water level and may be filled within minutes. Rubber dams do not require much money and may be a simple method of flood control which is extremely simple to install and mobilize [39].

3.2. Water supply management

3.2.1. Role in irrigation systems

Rubber dams are widely employed in enhancing supply management and irrigation. Thanks to their ability to hold water, they are used in constructing reservoirs and guaranteeing water supply for agriculture during droughts. This is especially helpful in areas with irregular rainfall patterns since the classic irrigation systems cannot supply water uniformly. Compared to conventional dams, rubber dams have straightforward and easily manageable structures that allow for installation in the shortest time possible and, therefore, use minimal time for construction. This rapid deployment is a great strength in locations where infrastructure for irrigation is required and is of paramount importance [39]. The manipulability of a rubber dam also enables variable water regulation based on the crops' precise requirements and the water supply's general state.

3.2.2. Contributions to domestic and industrial water supply

Besides the irrigation, rubber dams may be used for domestic and industrial water supply. These reservoirs act as a source of stored water and supply the water needs of people and industries. This is especially useful when little water quantity is available or water supplies are sporadic. The fact that it is possible to manage when the water stored in these reservoirs will be released enables efficient use of water by the demand. However, there is some information regarding the applicability of rubber dams for domestic and industrial water supply, even though no case studies are in the documents concerned [56]. Certain concepts can be developed because a rubber dam can create a powerful water supply system for storage and distribution for domestic or industrial purposes [57]. More investigation is warranted to understand how widespread these uses are and the practical appropriateness of the utilization.

3.3. Hydropower generation

3.3.1. Potential for energy generation

Inflatable dams, commonly called rubber dams, can be applied in hydropower generation, especially in developing miniature projects. These designs enable the establishment of variable head hydropower systems in which the water height is adjusted using a balloon to expand or shrink the dam. A unique characteristic of this system is its head, the capacity of which is adjustable to accommodate variable water flow to continue generating energy. Inflation and deflation also make it easy to under-take operational and maintenance costs, thereby cutting flood damage costs. In addition, they can be constructed freely and are very suitable for the construction of dams in hilly lands or areas with steep slopes, where the construction of normal dams presents serious difficulties. This makes them a perfect candidate for SHP projects, crucial in decentralized power production [58].

3.3.2. Comparison with traditional hydropower projects

Nonetheless, rubber dams are preferable to conventional hydropower projects (HPPs)in particular situations [59]. They are less cumbersome to build and, as such, are cheaper compared to larger-scale ones. Their design enables them to be modified to accommodate fluctuating hydrology characteristics or other site constraints. However, conventional HPPs have considerably greater head and flow and produce more energy [60]. A comparative study of rubber dams with the other types of diversion weirs for SPHS in India revealed that the life cycle cost of rubber dams is higher than other options [61]. This illustrates the feasibility of rubber dams for SHP developments where big conventional dams cannot be built or are unnecessary. However, due to the lack of initiatives for employing rubber dams in hydropower projects in India, the scope for their use needs to be explored more thoroughly to understand their possibilities and major concerns [58]. This point is also valid for both traditional and rubber dams, except for the differences in such aspects as sediment transport and disruption of ecosystems. Although the given documents are not rich in comparing the impacts of the environment, more research should be conducted to support safe and effective hydropower.

3.4. Additional applications and considerations

Although the paper provided here mainly elaborates on flood control, water supply, and hydropower generation, rubber dams are also used in other sectors. They are employed in tidal barriers, environmental improvement schemes, and recreational structures. Their application in cold, even at –40°C indicates their versatility and possibilities in various climate conditions. However, one major drawback is that they are easily scratched or spoiled with other pointed objects or acts of vandalism. Some of the risks have been addressed in the following ways: Ceramic chip coating and stainless-steel mesh have been used to counter this effect. They need to adapt permanently improved technology to improve the longevity and elasticity of rubber dams, thus also diversifying the fields of application. The rubber dam's effects on sediment transportation and river bodies are another factor beneficial for certain applications. However, the negative effects need further investigation

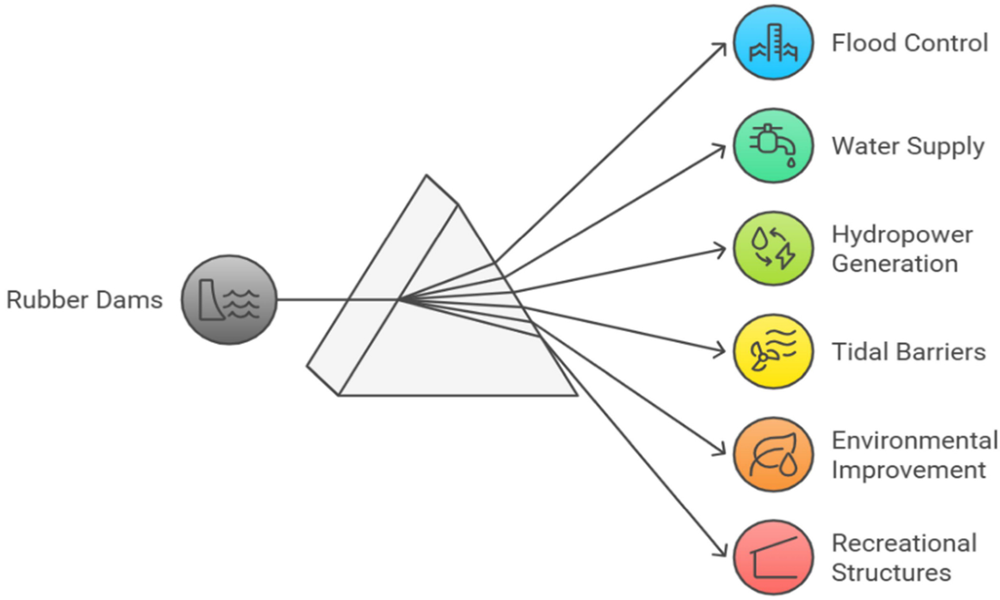

Fig. 5. Application of rubber dams.

to minimize adverse effects [62]. The papers form the basis for characterizing the versatile uses of rubber dams. However, more research is required to realize the full potential of use apart from being a warm water supply, while solutions to the challenges that arise need to be found. Unexpected and promising uses of this product include using rubber dams as components within larger water management systems. Fig. 5 shows the multifaceted application of rubber dams.

3.5. Design and application limits

The effective use of rubber dams depends on the observance of special technical and site-associated design constraints that determine the operation range of these dams. Dimensionally, rubber dams are normally made with lengths of stay 100 meters, but specially made membranes may even be made up to 200 meters wide. The height of dams is kept at a relatively low height of less than 5 meters in normal use, although special designs may have a height of up to 10 meters. These dimensional parameters indicate the structural constraints of reinforced rubber membranes in hydraulic pressure. Hydraulic Capacity: In terms of hydraulic capacity, rubber dams are best used in low-to-moderate head conditions and are intended to be completely deflated when in a major flood to permit the continued passage of high flows, thus avoiding structural damage [62].

Another important operational constraint is related to the management of sediment and debris; although the deflation capacity can be used to flush the sediment and minimize siltation of the reservoir in relation to fixed structures, even the rubber dams can have difficulties in rivers with very high sediment rates or with critical boulder motion during flooding. The membrane material in itself also places further constraints, such as vulnerability to UV degradation, temperature extremes, and abrasion by debris-contaminated flows. These conditions require site-specific hydrological and geotechnical analyses to define whether a rubber dam suits a particular river system, and the conditions that are considered inappropriate are a highly unstable channel with a rapid erosion or deposition

Table 4. Summary of rubber dam applications, purposes, and examples.

Application	Purpose	Example	References
Flood Control	Mitigate flooding by adjusting water flow and storing excess water.	Hong Kong's 20 rubber dams for flood management.	[54–56]
Irrigation and Water Supply	Store water for agriculture and domestic/industrial use during dry seasons.	Used in Bangladesh and other regions with seasonal rainfall variability.	[39, 56]
Hydropower Generation	Enable small-scale hydropower with adjustable head and flow.	Suitable for decentralized energy in hilly or remote areas.	[58–61]
Ecological and Recreational	Improve water quality, support ecosystems, and enable recreational activities.	Used in tidal barriers, urban river restoration, and community fishing projects.	[62]

rate, high flow velocity, or a place where debris loads may puncture the membrane. The working life, usually 15–20 years in favorable conditions, is also a design factor compared to concrete structures that are permanent and demand planning of long-term maintenance and a replacement of the membrane[63]. Table 4 show the summary of rubber dam applications, purposes, and examples.

4. Challenges and limitations of rubber dams

Rubber dams, while offering versatile applications in diverse sectors, face several challenges and limitations that hinder their widespread adoption and optimal performance [63]. These limitations span technical, environmental, and regulatory aspects.

4.1. Technical challenges

Among the key technical issues is that the technology can be easily disposed and has limited lifetime, which is also natural. Rubber dams are inflatable and when opened they are exposed to the environmental factors including radiation, sunlight heat, temperature change and abrasive materials deposited by water, which lead to rubber degradation. Consequently, this demands that the structures be inspected regularly and refurbished to determine their current status and prevent massive falls [64]. The intensity of service and occurrence of the maintenance are subject to conditions like the design of the dam, the characteristics of the material and the circumstances under which the dam operates. As an example, dams built in the area and particularly at the Arctic region where temperatures may drop to –40 °C, are to be built out of various materials and maintained under special regulations that accommodate the influences of the freezing and thawing process. Moreover, it can be challenging and rather costly to fix the damaged areas. On certain occasions, it can require specialized equipment or labor [65]. One of the biggest shortcomings of using rubber dams is that there is no proper professional staff and practices that will facilitate maintenance and avert the occurrence of faults in the rubber dams which will contribute to the fact that rubber dams is only good to last not even up to twenty years before becoming obsolete [64].

4.2. Environmental concerns

Concerns arising from the construction and operation of rubber dams are the environmental effects of the dams. As such, benefits and related changes in biotic and abiotic communities pose a great concern regarding ecosystem impact. Regarding the natural water flow regime, it is evident that this resource's manipulation can negatively impact fish migration, spawning, and general health. The elements such as water depth and velocity also modify the riparian vegetation and probably other sensitive ecosystems [66]. The building process of structures is also known to disrupt habitats and cause soil erosion. In addition, if the dam leaks, the chemicals or contaminants potentially produced throughout the dam's useful life or during the degradation process affect water quality [67]. The sediment input upstream of the DAM, subsequent by sediment trapping, likewise changes the balance of sediments in the river system [68].

Measures that can effectively control these impacts are as discussed below: The four processes include choice of the location, reduction of the construction impact, utilization of eco-friendly construction, and design. It is also important to incorporate ecological factors into decisions made at the dam operational body or the management organization [69]. This also involves measures for securing or reconstructing ecological water regimes, such as the controlled release of water to replicate stream flows. They concluded that quantitative monitoring of natural and waste waters and hydro-biological and hydro-chemical indicators is critical for evaluating impoundment and regulating its effects and utilization. At times, fish passage structures are incorporated in designs, thereby reducing the impacts of dams on fish movement [65].

4.3. Regulatory and policy framework

Other issues are unique to regulatory and policy concerning rubber dam projects. Getting permits or actual regulations necessary for operation is a time-consuming and convoluted process locally and nationally. These requirements are variable depending on the geography, size, purpose, and probable downstream effects on the ecosystem and society. There are always some pretty huge regulatory challenges that must be endured in the process, and navigating them often consumes a lot of time and money and may also need an expert touch. In addition, situations such as no distinctive protocols or no definite protocols in certain parts of the globe contribute to confusion and challenges. Permitting may be made more complicated by questions of water rights, ownership of land through which the water flows, and possibly with other water users [65].

Most respondents disclosed a definite need for supportive policies to ensure the implementation of rubber dam projects. Owning the following policies can make the feasibility and success of rubber dam projects much higher: Policies that facilitate the process of permitting; Policies that encourage incentives for sustainable rubber dam design; Policies on inter-stakeholder cooperation. Moreover, major policies warrant lifeline and repudiation for the sustainability of dams and the effective elimination of environmental vices [70]. Therefore, the regulatory and policy factors are essential in addressing the challenge of the regulatory and policy constraints to rubber dam projects through clear and consistent provisions to support these projects. Fig. 6 shows the challenges and limitations of rubber dams. Table 5 show the challenges and limitations of rubber dams across technical, environmental, and regulatory domains.

5. Case studies and practical implementations of rubber dams

Numerous rubber dam projects have been implemented worldwide, demonstrating their versatility and effectiveness in various applications. However, the success and challenges encountered in these projects highlight the importance of careful planning, design, and management. Zhang et al. [64] present useful lessons gained over 35 years of management

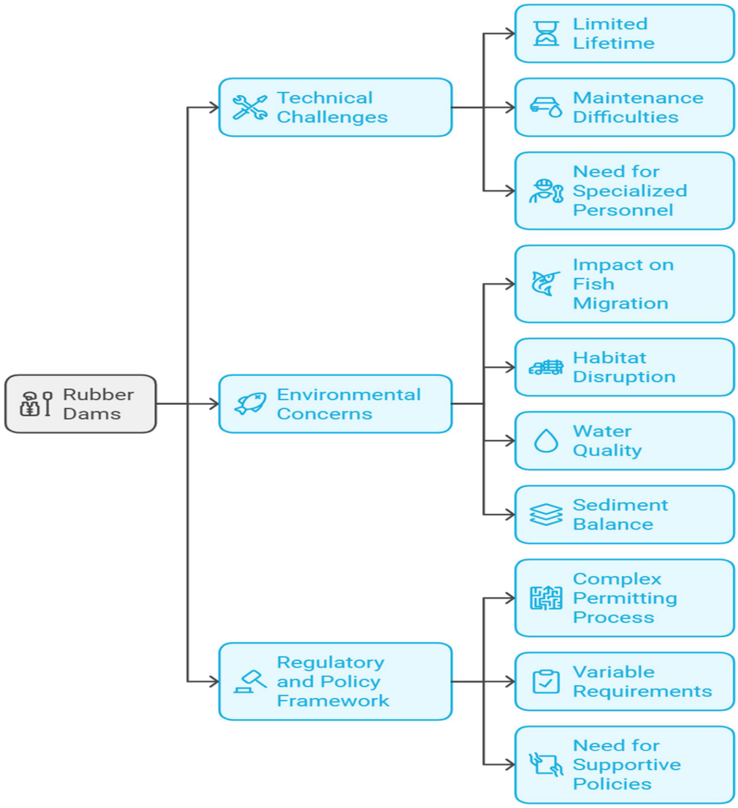

Fig. 6. Challenges and limitations of rubber dams.

Table 5. Key challenges and limitations of rubber dams across technical, environmental, and regulatory domains.

Challenge Type	Specific Issues	References
Technical	- Limited lifespan (∼20 years); degradation due to UV, temperature, and abrasion.	[64, 65]
	- Requires specialized maintenance and monitoring.	[65]
Environmental	- Alters natural water flow, sediment transport, and aquatic habitats.	[66–68]
	- Can impact fish migration, spawning, and riparian ecosystems.	[66, 68]
Regulatory and Policy	- Complex permitting processes and lack of standardized guidelines in some regions.	[65]
	- Water rights, land ownership, and stakeholder conflicts may arise.	[65]
	- Need for supportive policies to incentivize sustainable dam design and operation.	[70]

of rubber dams in Hong Kong. The findings are based on interviews with experts and practitioners in the context of rubber dam projects and an analysis of work done on a recent dam in construction, providing a study of the aspects of rubber dam projects. These considerations represent the focus of this research, which indicates that the simplicity and flexibility of the structure, along with the dependability of the chosen dam, should be considered when selecting applications. This study reveals that management practices play a major function in contributing to the sustainability of rubber dam projects.

The other case is the Rio Salado Town Lake in Tempe-Arizona [66]. Procedures relating to the creation of a large urban lake using inflatable rubber dams are involved in this project, and this has raised possibilities of the following effects on groundwater; thus, a subsequent management plan is needed [66]. The work is aimed at revealing the inefficiency of the generalized approach. It underlines the importance of considering specific conditions at a certain site and designing individual applicable solutions for probable problems.

Conversely, the case of a ground slip during the HDPE pipe installation for coal refuse impoundment in Eastern Kentucky [71] presents issues with the ground condition or construction techniques that may be encountered in designing or constructing pipelines. The slide during the pipe installation affected the pipe, so it was essential to undertake some rear scenes before the end of construction and when in operation [71]. The example outlined in this case study shows how keying into a site investigation and risk management tools reduces other challenges usually encountered in construction.

The Egyptian case of the Aswan High Dam project could further demonstrate how project delivery can be effective during a national emergency. Four approaches are outlined, and ten factors for success are presented to recognize that the project was successful despite the adversities [72]. This paper focuses on the need to develop strategies that help counteract obstacles in project management to achieve the desired project outcomes.

This paper's case studies have different contexts, opportunities, and challenges. However, they all confirm what has been argued in this paper that the planning, designing, and management of rubber dam projects must be addressed because failure and its attendant risks cannot be overruled. Knowing these and other projects' successes, difficulties, and challenges can help guide the use of this highly flexible technology and enhance its future performance. Future studies will be required to examine more projects involving more geographical locations, environmental conditions, and applications to recognize the further factors affecting the success and difficulties of rubber dam projects. This includes further assessment of the effects of rubber dams on the environment and the efficiency of various measures taken to try and curb them. In the same respect, additional research on the regulatory and policy environment of rubber dam projects in different areas would assist in defining the leading practices to increase the efficiency and efficacy of the permitting process. Table 6 show the overview of practical implementations and lessons learned from rubber dam projects worldwide.

Table 6. Overview of practical implementations and lessons learned from rubber dam projects worldwide.

Case Study	Location	Key Focus/ Application	Main Findings	References
Hong Kong Rubber Dams	Hong Kong, China	Flood control, urban water management	Over 35 years of operational experience shows that simplicity, flexibility, and proactive maintenance are key to long-term success and reliability.	[64]
Rio Salado Town Lake	Tempe, Arizona, USA	Urban lake creation, groundwater interaction	Highlights the need for site-specific assessment and management plans, particularly regarding groundwater impacts and urban hydrology.	[66]
HDPE Pipe Installation for Coal Refuse	Eastern Kentucky, USA	Construction risk, ground stability	Underscores the importance of thorough site investigation, risk management, and adaptive construction techniques to prevent failures.	[71]
Aswan High Dam Project	Egypt	Mega-project delivery under national emergency	Demonstrates effective crisis management, strategic planning, and stakeholder coordination for successful large-scale dam implementation.	[72]

6. Future directions and research needs for rubber dams

This section of the paper goes deeper into the future and research requirements in relation to the rubber dams, touching on the new technological trends and finding out the gaps that are critical in the area of water resource management. The scarcity of information in the given requires a generalized approach, which implies the establishment of links between the already known information on rubber dams and the large picture of the water resource management development.

6.1. Emerging trends in rubber dam technology

The new trends in the technology of rubber dam are making a new contribution to the management of water resources and the environmental safety. The following possible trends can be deduced:

6.1.1. Smart materials and sensors

The use of smart material and sensors in rubber dams is one of the different opportunities that could take place in the future. These advances can introduce the capabilities of continuously monitoring the conditions of the dam including the levels, pressure, and structural conditions [73]. This data may improve the functioning of the dam and foresee the imminent failures, but failures are not always common. Such monitoring systems are supposed to be able to provide hydrological modeling information and support water resources as well [74].

6.1.2. Improved durability and longevity

A research is likely to be conducted to enhance the lifetime properties of rubber dam products. This involves investigation of possible polymer combinations, additives, and procedures of shielded surfaces against environmental parameters such as UV radiation, temperatures and chemical wear and tear [75]. The extra years of the lifespan of the dams would result in low use of maintenance costs and high stability of the dams.

6.1.3. Modular and adaptable designs

Future rubber dam designs can be more simple to install and remove to other locations and work situations. This may include coming up with modular elements of a system which could be joined and separated in such a way that there is variation in the size, height and application of the dam. The buildings might also be designed using modular designs to facilitate the installation and maintenance procedures [12].

6.1.4. Integration with renewable energy

The possible implementation of the rubber dams is the integration of the RE technologies, such as hydraulic power generation that can be used in the water resource management [76]. Scientifically, a study can be conducted on the most appropriate way of constructing dams that are highly productive in terms of energy and with a relatively minimal negative environmental impact. This may include the creation of search key features like new designs of turbines or the storage process.

6.1.5. Advanced control systems

Subsequent rubber dams might be embedded with advanced control systems to adjust their operation and discharge strategies [77]. This could entail incorporating AI and/or

ML to forecast the water demand and adapt the dam's functioning [76]. These systems could enhance the rational utilization of water resources and decrease the potential for water emergencies.

6.2. Research gaps in the field of water resource management

The paper highlights several research gaps in water resource management, several of which are directly relevant to rubber dam technology:

6.2.1. Real-time data integration and adaptive mechanisms

The availability of systems that can address the risks associated with the social and economic factors and climatic variations in real time and with adaptive mechanisms in relation to the changes is one of the existing vulnerability issues in the water resource management [76]. This is particularly evident in the case of rubber dam operations where monitoring systems, feedback control systems can make the system much more reliable and effective.

6.2.2. Hybrid modeling approaches

Nonetheless, it can be observed that the further integration between mechanical optimization methods that are used when investigating intricate systems with intelligent technologies of the modern times is required [76]. This would assist in producing better and deeper outcomes on water-resourced evaluation as most features can be addressed by the two approaches. The technology of rubber dam might combine hydraulic simulation and AI-based predictive modeling to optimize the functioning of the dam and its risks management [78].

6.2.3. Validation across diverse conditions

The existing water resource management models have not been confirmed in wide variety of conditions of hydroclimatic conditions [79]. They are therefore limited in terms of applicability and usefulness in areas where there is change in precipitation and harsh weather. Further research is needed to ensure the validity of rubber dam models and management strategies in different situations.

6.2.4. Integration of ecological and economic considerations

Notably, science and practice of water resources management need more ecological and economistic approaches [80]. This plays a major role in the perception of water utilization and the likely effects to the natural setting. It, in the case of rubber dams, involves determining the impacts of the construction and operation of the dams on ecology, availability of water, and electricity that the dams will produce [81].

6.2.5. Capacity building and knowledge transfer

It is argued that sound water resource management is premised on powerful institutional capability and effective mechanisms of transforming know-how [82]. In this, energy is put on instilling early technologies and practices in water resource management and engineering to the key persons. The training that concerns rubber dams should deal with designing, building, running, maintaining, and safety of the dams [83].

6.2.6. Addressing unknown unknowns

The expansion of the dimensions of climate change introduces uncertainties, including unknown unknowns, to the process of water resource management [84–87]. Additional knowledge is still needed in terms of such risks and the most effective way of reducing such risks in water resource systems, and coming up with a process of integrating resilience measures in water systems. In the case of rubber dams, this must contain the impacts of the occurrences. like floods and droughts influence the behavior and safety of the rubber dams. The Fig. 7 illustrates the future trends and research requirement of rubber dams.

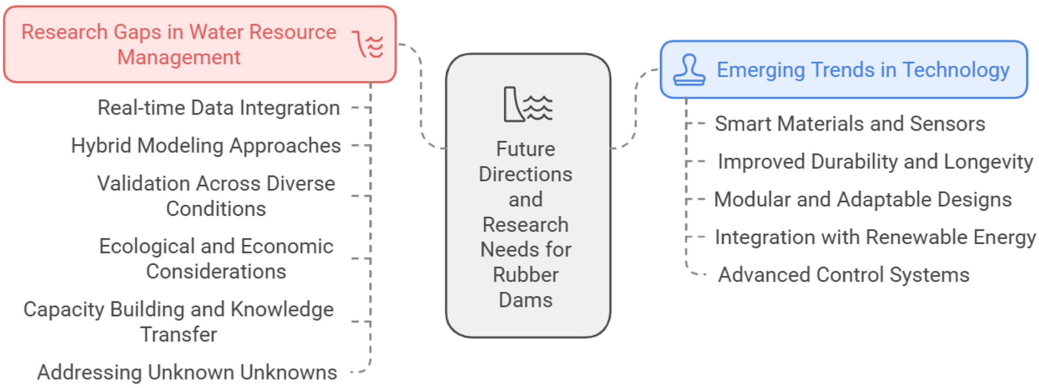

Fig. 7. Future directions and research needs for rubber dams.

6.3. Methodological considerations and empirical evidence gaps

Synthesized findings in this review are based on the systematic search of the scientific databases (Scopus, Web of Science, and Google Scholar) using such keywords as “rubber dams”, “inflatable dams”, “flood control”, “water storage” and “sustainable water management”. The search was restricted to peer-reviewed articles, conference proceedings, and technical reports in the English language published. Inclusion criteria were made based on studies providing original data on rubber dam design, performance assessment, environmental effects, or case study applications and excluded opinion articles, non-technical articles, and studies that reported on other non-relevant applications of rubber dams (e.g., rubber dams). Articles retrieved were analyzed thematically to reveal common themes with regard to applications, benefits, challenges, and geographical distribution, and quantitative synthesis was used in cases where similar types of data were found. One of the critical gaps that were discovered during this review process is that there is a relative lack of long-term empirical ecological monitoring data.

As an example, a five-year study of cascade rubber dams on the Huangshui River in China in the Qinghai Province contains useful quantitative evidence on the response of the aquatic ecosystems. The experiment reported a strong hydrological change, which primarily occurred during high-flow periods, with complicated biological outcomes: although plankton biodiversity and biomass rose 8.0 and 1.8 times, respectively, and fish and benthic animal biomass rose 3.2 and 2.1 times, respectively, species richness decreased by an average of 30%. It is interesting to note that native species were totally substituted by exotic ones, benthic communities changed toward singularity, and greenhouse gas emissions (N_2O and CH_4) induced by impounded lands were 10.1-fold [84–87]. The given findings make the case for the importance of implementing rigorous, longitudinal ecological evaluation into the agenda of future studies on rubber dams, beyond the technical or even financial analysis to comprehensively describe the environmental trade-offs. The way forward in future research has enhanced the adoption of standardized monitoring procedures in different hydroclimate areas to develop a stronger evidence base to support the sustainable implementation of rubber dams [87].

6.4. Statistical analysis

The statistical analysis applied to this research involved the use of the data collected in the previous studies of rubber dams, which has shown that there are some key trends. The majority of the studies (76%) were focused on the general ideas that were associated with rubber dams, including design principles, materials, and theoretical foundations. By comparison, a smaller of studies (24 %) were dedicated to single case studies which involved practical examples and operational assessment of rubber dams in different regions. The distribution of research activities was also very clear, with a significant concentration in the Asian region, which represented 78% of the reviewed studies. This is an act of the area being in the forefront when it comes to the production and use of rubber dams. Comparatively, those studies were in other continents were much lower: Africa contributed 14% of the researches, North America and South America only contributed 4% of the total researches. Fig. 8 presents the visual representation of the geographic distribution of the research and displays the findings made.

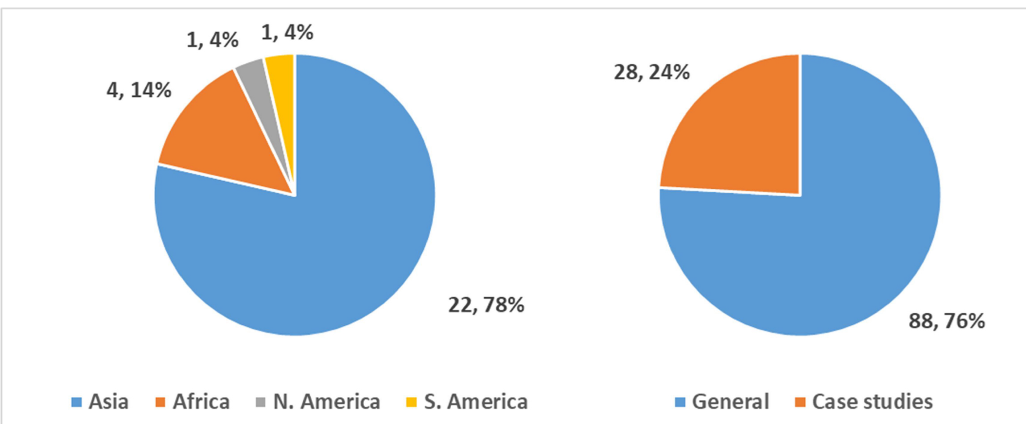

Fig. 8. Statistical analysis, Left- According to the area of the study, Right- According to the implementation whether general or case study.

The statistical analysis, which involved the analysis of the year the study was implemented in the last 15 years, demonstrated a substantial change in the emphasis on the rubber dams especially on the last ten years. The data was expressed that showed that there was a significant rise in research and interest in rubber dams since 2020. This pattern may indicate the increased awareness of the significance and possibilities of rubber dams in water management, presumably the technological progress, new environmental circumstances, and modified infrastructure requirements. Fig. 9 gives a representation change by showing that the 2020 and later volume of studies is higher than the previous half of the 15 years.

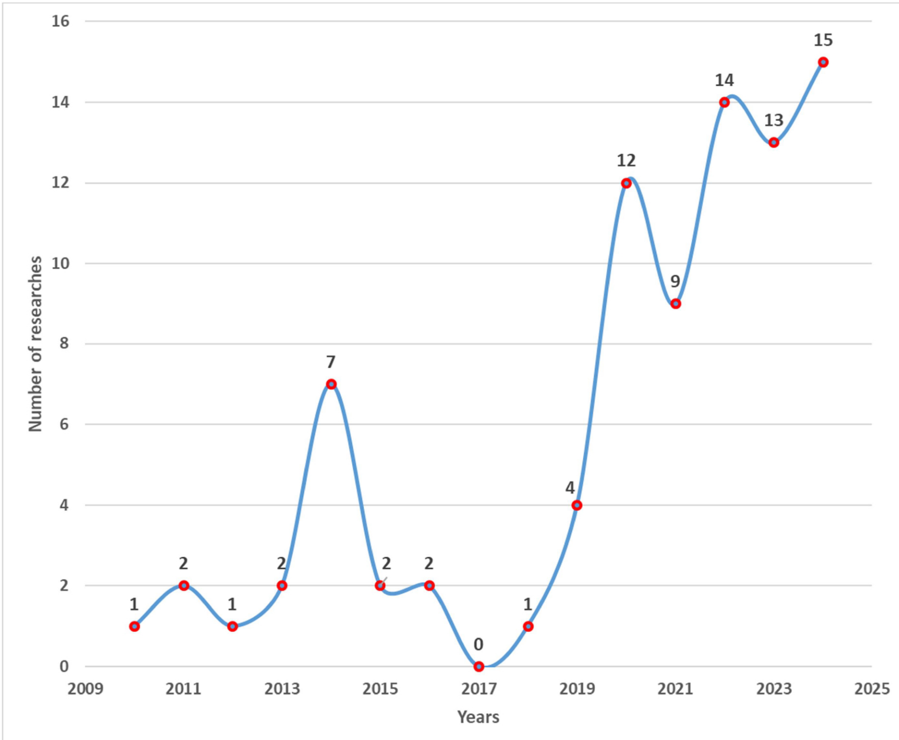

Fig. 9. Statistical analysis of the volume of studies conducted from 2009 to 2020.

7. Conclusion

Rubber dams are a ground breaking and environmental sustainable technology in water resource management around the world as it has been successful in addressing key challenges such as water shortages faced by 2 billion humans in the world and in floods whereby this technology has resulted in the loss of economic value amounting to 100 billion dollars in 2020. They are an essential adaptive solution due to their unique versatility, cost-effectiveness and reduced environmental footprint, particularly in regions that experience variable weather conditions and less infrastructure budget. These buildings are very much consistent with the objectives of sustainable development in a doubtful climatic era because they lead to the dynamic management of water levels, irrigation, and supply of water and lessen flood hazards as experienced in successful projects like the 20 rubber dams in Hong Kong.

The evidence that is synthesized in this review highlights a complex value of rubber dams as well as showing significant trends in research and implementation. It is noteworthy that 76 % of the available literature is devoted to general design and theoretical principles, as compared to 24 % of the research devoted to the real-life case study, which means that more applied research is required. Geographical distribution: 78% of research based on rubber dams originates in Asia, and much less in Africa (14%) and the Americas (4%), thus showing regional differences in research and implementation. Although they have some benefits (reduced costs, improved local irrigation, and recreational and ecological services), rubber dams are facing the same challenges that have affected them since their beginning, which include a limited life cycle of about 20 years of operation, exposure to environmental degradation, and difficulty in regulation boundaries depending on the region.

In the future, there seem to be promising trends in the field of increasing the durability, efficiency, and versatility of rubber dams through the integration of new technologies, including smart materials, real-time monitoring, AI-driven control systems, and modular designs. The future of such work should focus on the validation of performance under different hydroclimatic conditions, policy and regulatory frameworks reinforcement, and enhanced stakeholder involvement. With sealing research gaps, broadening geographical use, and adopting innovation, rubber dams could become even more central in guaranteeing tenacious and fair water security globally so that the prospects of their use are not underestimated in the context of increasing environmental and societal pressures.

Author contributions

Conceptualization, L.A.; methodology, L.A. and K.A.; Formal analysis, N.D.; Investigation, N.T.; resources, A.N. and L.A.; Data curation, K.A. and N.D.; writing—original draft preparation, L.A.; writing—review and editing, A.N. and N.T.; visualization, K.A.; supervision, L.A and N.D.; Statistical analysis, A.N.; Software, L.A., N.T., and N.D.; funding acquisition, Nill. All authors have read and agreed to the published version of the manuscript.

Competing interests' policy

We declare that the authors have no competing interests as defined by Nature Research, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Dual publication

The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration (from you or one of your Contributing Authors) by another publisher.

Authorship

We confirm the corresponding author has read the journal policies and submit this manuscript in accordance with those policies.

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Data availability

Data is provided within the manuscript.

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