

Review

Leaky Dams as Nature-Based Solutions in Flood Management Part I: Introduction and Comparative Efficacy with Conventional Flood Control Infrastructure

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Abstract: Natural flood management strategies are increasingly recognized as sustainable alternatives to conventional engineered flood control measures. Among these, leaky dams, also known as woody debris dams or log dams, have emerged as effective nature-based solutions for mitigating flood risks while preserving essential ecosystem services. This review traces the historical evolution of leaky dams from ancient water management practices to contemporary applications, highlighting their development and adaptation over time. It presents a comparative examination of leaky dams and conventional flood control structures, outlining their respective strengths and limitations across ecological, hydrological, and economic dimensions. The review also introduces a conceptual classification of leaky dams into naturally occurring, engineered, hybrid, and movable systems, showing how each form aligns with varying catchment characteristics and management objectives. By synthesizing foundational knowledge and strategic insights, this paper establishes a theoretical and contextual framework for understanding leaky dams as distinct yet complementary tools in integrated flood management, laying the groundwork for further technical evaluations. The findings offer valuable insights for end users by highlighting the potential of leaky dams as integral components of sustainable flood management systems, elucidating their roles in mitigating flood risks, enhancing water retention, and supporting ecosystem resilience.

Keywords: flood management; leaky dams; nature-based solutions; sustainability



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1. Introduction

Floods are a major driver of both anthropogenic and ecological destruction, causing widespread disruption to socioeconomic stability and severe damage to ecosystems on a global scale [1,2]. In South and East Asia, the situation is especially dire, with approximately 1.2 billion individuals living in flood-prone areas [3]. Countries such as China and India exemplify this vulnerability, accounting for over one-third of the global population exposed to flooding [3]. In China alone, flooding impacts over 50% of the population and 66% of

its landmass annually, resulting in GDP losses of approximately 1.4%, a stark contrast to developed nations such as the United States [4]. The increasing frequency and severity of floods in these regions highlight the urgent need for robust mitigation strategies and adaptive measures to address this escalating crisis.

In recent decades, urban planning and other socioeconomic factors have significantly impacted flood management, particularly in low-income nations where resources for flood control are scarce [5]. Flooding causes significant losses in property and crops, as well as economic disruption and infrastructural damage in these countries [6]. For instance, research by AL-Hussein et al. [7] found that several communities in the northern Iraqi Khazir River basin are at risk of annual flooding, particularly where dwellings are constructed with stone and mud, which are more susceptible to water damage than those built with stone and cement. The study further found that houses made of stone and mud are highly prone to collapsing over time as they provide minimal defense against flooding. Flooding often incurs a financial cost that extends beyond immediate damages, as recovery efforts may require funding from more profitable sectors that would otherwise drive economic growth and development [8]. This reallocation of resources can lead to prolonged economic challenges, particularly in underdeveloped regions where resources are already limited. Continual flooding also causes communities to lose their modes of employment and experience increases in the cost of goods, which in turn weakens their purchasing power [9]. Thus, it is evident that these consequences highlight the urgent need for comprehensive flood management strategies that integrate physical, social, and economic considerations to mitigate the impacts of flooding, protect vulnerable communities, and ensure long-term resilience against future flood events.

Similarly, the rapid rate of urbanization in recent decades has resulted in the construction of drainage networks and the clearing of vegetation, disrupting natural water flow and absorption processes [10–12]. The probability of severe flooding increases significantly when cities expand into flood-prone areas with inadequate infrastructure to withstand intense weather conditions [13]. For instance, large areas with impermeable surfaces made of asphalt and concrete decrease hydrologic response times and elevate the risk of flooding [14]. A study in Toronto highlighted this link between urban expansion and flood risk, revealing that urbanization significantly increases peak discharge, shortens response times, and raises surface runoff and river discharge rates, based on an analysis of land use data from 1966 to 2000 and six impervious surface scenarios (0% to 100%) [15]. Increased urbanization alters natural drainage patterns and streams, often leading to more intense and frequent floods. In addition, deforestation, which leads to land use change [16], is one of the main factors for flooding in developing areas [17].

Currently, several major flood management strategies are used globally to lower the danger of flooding and lessen its effects. These consist of both non-structural measures such as flood warning [18], flood forecasting systems [19], and floodplain zoning [20], and structural measures such as dams [21], reservoirs [22], levees [23], and dikes [24]. Yet, research demonstrates that both structural and non-structural flood control methods, such as dams, reservoirs, levees, and dikes, have several drawbacks, largely because many of these systems are based on design standards developed decades ago and are not well suited to current environmental and urban realities. These legacy approaches are increasingly inadequate for addressing contemporary environmental changes such as climate change-driven extreme rainfall events, rapid urbanization, increased impervious surface coverage, and altered land-use patterns. These limitations often result in insufficient protection against modern flood risks, which include more frequent and intense flood events, unpredictable rainfall patterns, and higher volumes of surface runoff due to loss of permeable ground. Such conditions can overwhelm traditional flood infrastructure, leading to overtopping of

levees, dam stress or failure, and increased flow velocity downstream. This may intensify flood impacts in both urban and rural areas, especially where floodplains have been disconnected or natural buffers removed. Issues in structural flood management techniques include the destruction of ecosystems, increased danger of flooding downstream, high maintenance costs, and dislocation of communities [25–29]. Similarly, non-structural flood management techniques pose problems with the accuracy of data, forecasting infrequent occurrences, and cost concerns [30].

Nature-based solutions (NBSs) for flood management have become increasingly popular as an effective approach to reducing flood risk while addressing the limitations associated with conventional flood management strategies [31,32]. Therefore, this review aims to provide a comprehensive examination of leaky dams (refer to Figure 1) as nature-based solutions for flood management, focusing on their historical evolution, design typologies, and comparative efficacy with conventional flood control infrastructures. By synthesizing the existing literature and case studies, this study seeks to elucidate the mechanisms by which leaky dams mitigate flood risks, enhance ecological resilience, and offer cost-effective alternatives to traditional engineering solutions. Additionally, the review highlights the benefits and limitations of various leaky dam designs, offering insights into best practices for their implementation and maintenance. Through this analysis, the review aims to inform policymakers, urban planners, environmental managers, and researchers, providing a robust foundation for the broader adoption and integration of leaky dams within sustainable flood management frameworks.



Figure 1. Representative leaky dam structures in a stream: (a) cross-sectional elevation under baseflow conditions, and (b) overhead view during a high-flow event [33].

2. Natural and Man-Made Flood Control Methods

Flood control techniques are typically categorized into two broad groups: natural and man-made. Natural methods include wetland conservation [34], ecological restoration [35], and forest regeneration [36]. Man-made methods are further divided into structural and non-structural approaches. Structural techniques involve physical infrastructure such as dams, levees, dikes, bypass channels, and floodwalls to control or redirect excess water [30,37,38]. Non-structural methods, by contrast, focus on land-use planning, early warning systems, and policy frameworks aimed at minimizing exposure and vulnerability without altering the physical environment.

In recent years, NBSs for flood control have gained vast attention and recognition due to their sustainable approaches towards the use of natural ecosystems to mitigate flood hazards [39]. NBSs, when compared with conventional techniques such as dams or levees,

prioritize recreating or restoring natural landscapes to absorb and redirect floodwaters [40]. Key NBSs for flood management and mitigation include ecosystem restoration [35], the creation of water retention areas [41], and the implementation of hybrid approaches [42]. The restoration of ecosystems focuses on enhancing or recovering ecosystems such as wetlands, rivers, forests, and floodplains [43]. These areas offer vital functions such as retaining water, decreasing surface runoff, and boosting the land's capacity to absorb and store water [44]. For example, the Cosumnes River Floodplain Restoration project in California, USA, where levee removal allowed floodwaters to spread over a larger area, demonstrates how recovering rivers' natural floodplains can greatly reduce flood risk while promoting biodiversity and ecological resilience [45].

Creating water retention areas is an effective way to manage floods, especially in urban and rural areas where excess water is a major issue [46]. Water retention areas, which use both natural and manmade methods to manage stormwater, are also known as hybrid flood control strategies [47]. These areas are designed to temporarily or permanently hold water during intense rainfall or elevated stream levels to reduce the risk of downstream flooding [26]. These areas include retention basins [48], constructed wetlands [39], excavated floodplains [45], and detention ponds [49]. Retention basins retain water permanently, improving water quality by removing particulate-bound pollutants and providing habitats through natural filtration [50]. Detention ponds store water temporarily before releasing it back into the drainage system after peak flow [51], while excavating floodplains creates extra storage space for floodwaters, allowing rivers to overflow into designated areas during periods of high discharge [51].

Artificial flood control methods provide protection to people and their assets, maintain economic stability, and build community resilience against the growing threat of floods. The effectiveness of man-made flood control strategies varies widely, depending on several factors, including the design, placement, and management of these systems [37,52]. In the study by Villamizar et al. [53], a mix of real data and modeling revealed that 27 leaky barriers in a lowland farming area lowered peak water flows by 22% and delayed flooding by up to five hours. The findings also emphasized that allowing water to drain faster through permeable barriers is key to handling multiple storms in a row. A similar study was conducted on Japan's G-Cans Project, an extensive underground flood control system in Kasukabe, Saitama. Since becoming operational in 2006, the system has been activated nearly 70 times during periods of intense rainfall, significantly reducing flood damage by almost two-thirds and decreasing the number of affected homes and areas [54]. Furthermore, the study suggests that to avoid additional flooding, the system can pump up to 200 m³/s (53,000 gallons) into the Edogawa River, which is located at a lower altitude, which emphasizes its effectiveness in times of extreme precipitation. These examples highlight the capacity of engineered flood control systems to deliver significant protection in their respective contexts; however, their effectiveness is closely tied to the scale, design, and environmental setting in which they are deployed. While such systems can offer substantial benefits in high-risk areas, direct comparison with nature-based solutions must consider contextual differences.

Man-made flood control techniques can be categorized into two groups: structural and non-structural. Several studies have identified that structural flood control methods carry the risk of structural failure and continue to pose persistent dangers. For example, research suggests that more than one hundred dam failures have occurred since the 1700s, resulting in significant environmental damage and hundreds of fatalities worldwide [55,56]. A study by Angelakis et al. [56] showed that in 1998, the midstream reaches of the Yangtze River experienced catastrophic flooding, which devastated provinces such as Hunan, Hubei, Jiangxi, and Anhui. It also caused the failure of 975 dikes along the river and its tributaries,

resulting in the deaths of over 3000 people. Furthermore, the economic losses from this disaster were estimated to be between USD 24 billion and USD 70 billion (in 2015 USD). This reiterates the possible failures of structural flood control measures and their acute impacts on people, livelihoods, and the economy.

Non-structural flood control techniques represent a multifaceted approach to managing flood risks. These approaches emphasize planning, policies, and management techniques instead of physical construction to mitigate hazards [57]. Recently, there has been increased focus on using technology to predict floods and notify communities in advance, allowing for timely evacuations and preparations [58]. For example, a study by Tabbussum and Dar [59] emphasizes the importance of the AI computing paradigm in modeling stream flow and its role in flood prediction models to mitigate the socio-economic impacts of flooding. The study showed that the best-performing model had a Nash–Sutcliffe Model Efficiency (NSE) of 0.968, indicating high accuracy, as this statistical measure compares predicted values to observed values, with higher values closer to one signifying better performance. Thus, it is evident that the inclusion of updated technology has improved both the efficacy of emergency systems and their ability to enable timely evacuations and preparedness measures to protect communities and infrastructure in times of floods. Furthermore, since non-structural approaches minimize their environmental impact and support structural solutions, they are often considered more sustainable.

3. NBSs vs. Traditional Engineering Solutions

NBSs and traditional engineering methods each come with their own set of advantages and limitations [60]. NBSs, such as reforestation, wetland restoration, and leaky dams, provide a holistic approach to flood management by integrating ecological benefits with water regulation [61]. NBSs tend to be less invasive and are designed to work with the natural landscape, offering multifunctional benefits such as habitat restoration [62], soil health improvement [63], enhancing biodiversity [64], improving water quality [65], and contributing to carbon sequestration [66]. NBSs can take time to become fully effective and often depend significantly on local environmental conditions and thorough planning processes. For example, Yarina [67] describes the Noordwaard “Living with Water” concept under the Room for the River initiative in the Netherlands, where 4450 hectares were strategically converted into a multifunctional floodplain by lowering existing dikes. This allowed the area to flood safely during high-water periods, significantly reducing flood risk while simultaneously restoring wetlands and creating habitats beneficial for wildlife, such as water buffalo and sea eagles. The initiative’s success was largely due to a strong understanding of local hydrological and socioeconomic dynamics, including comprehensive stakeholder engagement and compensation strategies for displaced residents.

On the other hand, conventional engineering methods such as levees, drainage systems, and dams are typically designed to address extreme flood conditions through standardized engineering practices, often providing more predictable flood control outcomes. While traditionally engineered structures effectively deliver targeted protection for areas facing high flood risks [68], it is important to recognize that their implementation timelines can be comparable to those of nature-based projects. Hence, the primary distinctions between NBSs and traditional methods may not lie in execution speed, but rather, in their ecological benefits, flexibility, and requirements for local environmental integration and stakeholder involvement.

For instance, Kuala Lumpur’s Stormwater Management and Road Tunnel (SMART Tunnel) has successfully avoided flooding in the city center on at least nine occasions since it started operating in 2007 through the prompt activation of its major flood mode (Mode 3) [69]. Severe storms trigger the SMART Tunnel to enter flood mode (Mode 3),

shutting it off to all traffic and allowing it to operate exclusively as a stormwater diversion system, efficiently redirecting excess water to prevent flooding in Kuala Lumpur's downtown area [70,71]. These conventional engineering flood control methods often prioritize flood management while giving little attention to ecosystems and their balance, which can result in long-term environmental harm, including habitat destruction and increased erosion [37,72]. Large dams, concrete barriers, and engineered drainage systems can disrupt water flow, block sediment movement, and destruct habitats, negatively affecting local biodiversity [55,73,74]. For instance, the Three Gorges Dam in China displaced over 1 million people and submerged approximately 1084 km² of land, including forests and farmlands [75]. Furthermore, these constructions can harm fish populations, reduce wetlands, and cause erosion while also disconnecting rivers from their natural floodplains. According to previous studies, the building of levees along the Mississippi River has lowered the natural flooding that replenishes wetlands, which has caused the annual loss of about 16 square miles of coastal wetlands in Louisiana [76,77].

On the other hand, NBSs promote the conservation and restoration of ecosystems. Methods such as leaky dams and reforestation aim to restore degraded landscapes, improve habitats, and boost biodiversity [78,79]. An example is the installation of over 170 large woody debris dams in Cropton Forest, as part of the "Slow the Flow" initiative aimed at natural flood management, as leaky dams help retain water, reduce erosion, and create diverse habitats for aquatic organisms [80,81]. By allowing water to flow naturally, NBSs help preserve the ecological integrity of rivers, wetlands, and floodplains, promoting biodiversity expansion and reducing the risk of flooding.

One major drawback of traditional flood control techniques, such as dams, levees, and floodwalls, is their linkage with high construction and maintenance costs, as these expenses can place considerable strain on a country's budget and make long-term sustainability challenging, especially in regions with fluctuating environmental conditions that may require constant adjustments or repairs [82,83]. For example, cost estimates from a review study by Aerts [84] show that the design type and reinforcement method significantly affect the cost of upgrading dikes and levees. According to this study, raising sea dikes costs around USD 20.8–25 million/km per meter in the Netherlands and USD 21.8–31.2 million/km per meter in European cities. Furthermore, in Canada, raising levees costs approximately USD 5.3 million/km per meter for typical levees and USD 1.9 million/km per meter for earthen levees. NBSs, however, are generally much cheaper to implement and maintain. Wetland restoration, reforestation, and leaky dams frequently use locally available natural resources such as timber and debris, and once set up, these structures usually require relatively little upkeep as the surrounding ecosystems themselves provide ongoing maintenance, reducing the need for costly human intervention [85,86]. Furthermore, features such as wetlands, forests, and floodplains can regenerate over time and adapt to new environmental situations, as NBSs rely on ecosystems that are naturally resilient to changing environmental conditions. However, traditional engineered flood control structures, such as large levees and dams, are typically designed to withstand extreme flood events, often with recurrence intervals of once every 100 years or even as high as once every 10,000 years [84]. Despite their effectiveness, the substantial costs associated with their construction and maintenance can be prohibitive. In contrast, leaky dams are generally suited for attenuating smaller-scale flood events with shorter recurrence intervals (e.g., up to once every 100 years). They are therefore more appropriate for managing frequent, moderate floods rather than rare, catastrophic events. As such, the implementation of leaky dams should be carefully contextualized within their intended hydrological design scope, with a clear recognition of their limitations in high-risk settings that demand stringent flood protection standards.

4. Overview of Leaky Dams

4.1. Historical Context and Evolution

Flood management has been an essential component of human society, experiencing remarkable evolution from traditional techniques to current advancements. The history of leaky dams is directly linked to ancient water management practices, in which communities employed natural materials to control water flow [56]. Research indicates that while the modern term “leaky dams” emerged from early 20th-century studies of beaver dams, natural structures built by beavers using logs, branches, and mud [87], the broader concept of using permeable, flow-slowing barriers dates back much earlier. Historical records and archaeological findings suggest that indigenous communities and early civilizations employed similar structures for water management and ecological purposes long before the terminology was formalized.

Furthermore, the Mesopotamians constructed canals and ditches to direct river water to their fields, thus improving agricultural productivity and facilitating urbanization [88]. The economic and social advantages of these systems were substantial, providing numerous benefits to their livelihoods. The Industrial Revolution signified a transformative period in flood management due to accelerated urbanization, modified land use, deforestation, and environmental deterioration. Urban expansion created extensive impermeable surfaces such as structures, roadways, and industrial facilities that greatly enhanced surface runoff and restricted natural water infiltration [89,90]. According to research by Konrad [91], the Northeast Branch of the Anacostia River has experienced a rise in the occurrence of daily outflows surpassing 1000 cubic feet per second, from one or two instances annually in the 1940s and 1950s to up to six occurrences per year by the 1990s. This shift illustrates how urban development has contributed to heightened maximum flow rates and more frequent flooding events. As a result, urban regions started facing rapid and more severe flood peaks due to lowered catchment response times [92]. Moreover, the alteration of ancient floodplains destroyed essential natural flood storage zones, thus raising the risk and severity of flooding [93].

With rapid urbanization, accessibility to raw materials such as steel and reinforced concrete facilitated the development of more advanced and resilient water management systems [94]. Major projects such as the Hoover Dam in the United States and the Aswan High Dam in Egypt illustrate the potential of large-scale engineering during the past decades [95,96]. These dams facilitated flood management, irrigation, and energy generation, substantially enhancing regional economies [97]. By the mid-20th century, environmental concerns arose, emphasizing the ecological disruptions caused by these large constructions, including habitat destruction and downstream erosion [98–100].

Research on natural log dams conducted in the 1980s demonstrated their considerable advantages for flood management and habitat development. This resulted in initial attempts utilizing simple wooden constructions to replicate these natural barriers, facilitating the development of current leaky dam designs [101,102]. In the 1990s and 2000s, the design of leaky dams progressed through standardized designs, incorporation into watershed management, and the utilization of various materials such as stone and brush [103]. This concept mainly focused on flood control, water quality, and ecological restoration [33]. Leaky dams, called woody debris dams or natural flood management structures, are now essential components of flood control strategies [104]. Today, leaky dams are tailored to specific flow rates and local conditions, making them widely used in river restoration and urban flood management projects [105]. The Slowing the Flow project in Pickering, North Yorkshire, United Kingdom, is a prominent example of successful leaky dam implementation. This project has demonstrated its efficacy in reducing downstream flood peaks, restoring ecosystems, and boosting biodiversity [106].

Currently, leaky dams are frequently incorporated into other natural flood management strategies, including reforestation, wetland creation, and floodplain restoration [107]. For example, in Crompton Moor, Oldham, UK, five dams were constructed to slow the passage of water before it reaches downstream communities. The initiative further included the planting of more than 2000 species of Sphagnum moss and 1500 trees to enhance carbon capture and restore peatland ecosystems, which suggested a comprehensive approach to ecological restoration and flood risk reduction [108]. With the increasing intensity and frequency of rainfall, leaky dams present a cost-efficient and environmentally sustainable alternative to conventional large-scale infrastructure. The evolution from the ancient irrigation systems of Mesopotamia to contemporary-designed leaky dams illustrates a transition from extensive, resource-demanding initiatives to sustainable and adaptive strategies. Leaky dams show a harmonic balance between flood management and conservation of the environment by modeling natural processes and integrating ecological concepts, hence assuring resilience against climate change.

4.2. Types of Leaky Dams

Leaky dams are a wide category of water management structures that can be grouped according to their materials used for construction, architectural methodology, durability, and installation techniques [94]. These structures have progressed from basic natural barriers to advanced designed systems for decades. The selection of the most suitable leaky dam type is influenced by the site conditions, management goals, and available resources, considering factors such as the geological and hydrological characteristics of the site (topography, stream size, flow characteristics, sediment load), construction access, and maintenance needs [103,109]. In Essex, UK, for example, leaky dams were built in Harlow and Thorndon Country Park using materials gathered from the area, including hardwood oak and fallen ash wood. This method had the lowest possible risk of damage to the environment and ensured that the materials would work well with the natural water conditions in the area, which made it easier to regulate the water during periods of intense rainfall. The successful implementation of leaky dams involves combining different dam types within a watershed to address various management challenges while maintaining ecological connectivity and natural processes. Figure 2 provides a typical cross-sectional view of a leaky dam. Elevations are denoted as z_n , and heights relative to the bed level (z_{bed}) are represented as h_n . The leaky dam becomes active when the water surface elevation (z_{water}) rises above the elevation of the dam's base (z_{base}). During simulations, the top (z_{top}) and bottom (z_{base}) elevations of the leaky dam remain constant. Therefore, variations in the water level (z_{water}) and bed level (z_{bed}) affect the dam's functionality.

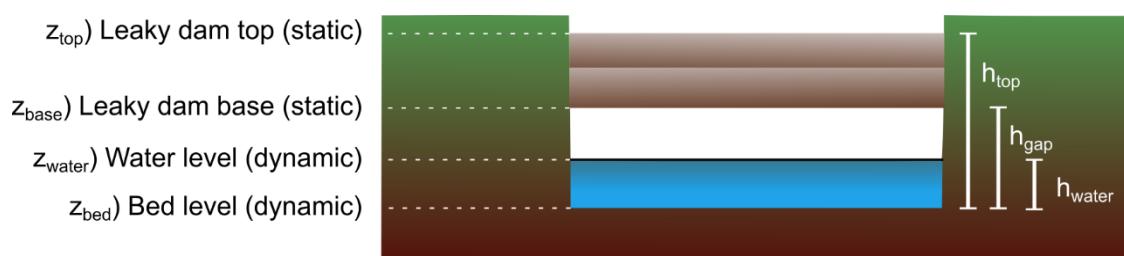


Figure 2. A schematic illustrating hypothetical cross-section of cells containing leaky dams [110].

Water managers can make sensible decisions about the implementation of various defective dam types by understanding their classification and characteristics. The selection and implementation of suitable leaky dam types are becoming more essential for sustainable water management strategies as the dynamics of watersheds become more impacted by climate change and urbanization pressures.

Table 1 outlines the special features of the major types of leaky dams classified based on the materials used. Brushwood and natural woody debris dams are best for ecosystem enhancement with abundant natural materials, while engineered wooden boards and rock barriers are suited for precise water flow control. Geotextile-assisted dams offer added stability and filtration, and hybrid designs combine materials for improved performance and flexibility.

Table 1. Comparison of different types of leaky dams based on materials used, structural features, contributions to flood mitigation, and ecosystem services.

Type of Dam	Materials/ Substances Used	Main Features	Contribution to Water Control/Flood Mitigation	Other Ecosystem Services	References
Natural Woody Debris Dams	Fallen trees, branches, Douglas fir logs	Semi-permanent; reduces flow velocity (~40%); promotes channel complexity	Slows surface flow, reduces flashiness in streams	Habitat creation, stream shading, sediment retention	Kraft and Warren [111]; Lo et al. [112]
Brushwood Dams	Twigs, live willow, coppiced hazel	Dense vegetative matrix; traps sediment; fosters riparian growth	Attenuates peak runoff by up to 30% in small catchments	Soil stabilization, vegetation regeneration, carbon capture	Fakhari et al. [113]; Frankl et al. [114]; Rotherham and Harrison [115]; Tahy et al. [116]
Wooden Board Dams	Oak, elm, cedar planks; treated lumber	Interlocking panels; adjustable flow; forms upstream pools Durable under high flow;	Flow regulation; delays runoff; improves channel storage	Fish passage, instream habitat, water quality buffering	Adamo et al. [117]; Piton et al. [118]; Timber [119]
Rock and Boulder Dams	Boulders, natural stone, compacted rockfill	geotechnical stability; permeable	High capacity for flood buffering; withstands strong hydraulic forces	Channel stability, aquatic habitat structure, erosion protection	Crane [120]; Degerman [121]; Lenzi [122]
Wood–Rock Hybrid Dams	Treated timber, large stones, aggregates	Interlocked structure; high sediment retention (60–85%)	Effective for 1:100-year events; smooths hydrographs in variable flow systems	Salmonid habitat, sediment balance, aesthetic integration	Piton et al. [118]; Al-Ruzouq et al. [123]
Geotextile- Assisted Dams	Geosynthetic permeable fabrics	Soil stabilization; improves filtration; limits particle migration	Enhances embankment resistance; supports drainage and overflow control	Reduces turbidity; supports embankment vegetation; improves infiltration	Allaire [1]; Basu et al. [124]; Tanasă et al. [125]
Seasonal/ Movable Dams	Inflatable rubber membranes, metal frameworks	Temporary deployment; collapsible or inflatable; repositionable	Provides short-term flood defense or storage during seasonal peaks	Minimal ecological disruption; fast recovery; wetland habitat preservation	Adamo et al. [95]

4.2.1. Natural Leaky Dams

Natural Woody Debris Dams

The foundation of leaky dam design has consisted of natural woody detritus dams, which are based on following beaver dams and naturally occurring log dams in streams. Usually, materials used in natural woody detritus dams are locally sourced and arranged to maximize stability while allowing controlled water movement, creating intricate flow patterns that maintain ecosystem connectivity, limit water flow, and serve as habitats that protect aquatic species and enhance biodiversity [111].

These structures can be strategically constructed across waterways using fallen trees, branches, and other woody materials, or they can form naturally. For example, in Spring Creek, Oregon, USA, a natural woody detritus dam resulted from the depositing of 20-foot Douglas fir logs across the stream channel during a storm [112]. A 3 m wide, 1.5 m high structure was formed as a result of the accumulation of additional branches and foliage over time, and this naturally formed structure reduced flow velocities by 40% and provided habitat for local salmon populations. In contrast, the River Tweed Conservation Project in Scotland is an important instance of strategic placement that involved the use of existing bankside trees to anchor fallen oak and birch trees in third-order streams. These semi-permanent detritus dams, which are 4 m in width, effectively contain sediment while allowing fish to pass.

Brushwood Dams

Brushwood dams, a type of leaky dam that is naturally occurring, are mainly made up of living vegetation, twigs, and small branches [126]. In headwater areas and minor streams with moderate flow volumes, these structures are particularly effective as they capture sediment and promote vegetation growth, which naturally strengthens the structure over time [127]. According to Frankl et al. [114], brushwood dams are most effective when installed across minor gullies with a maximum depth of one meter, and they are most effective in channels with slopes between 5% and 12%. Their height is maintained at less than one meter, with the upstream side permitting water to pass while the structure retains sediment behind it [128]. In the Yorkshire Dales, UK, brushwood dams measuring 2 m in length were constructed by weaving locally harvested live willow branches between posts, creating living barriers that have reduced peak volumes by 30% during storm events [115].

In the same way, brushwood dams constructed from coppiced hazel in the New Forest National Park, UK, generated dense matrices that are 1.5 m high and 3 m wide, effectively capturing up to 60% of suspended particulates during high-flow periods [116]. A study by Fakhari et al., [113] demonstrated that brushwood dams (BWDs) on forest road fill slopes significantly reduced runoff by 57% and sediment concentration by 23%, highlighting their effectiveness in controlling erosion and runoff, particularly when combined with conservation treatments and planting seedlings such as *Alnus glutinosa* and *Salix alba*. These structures demonstrate substantial potential for ecosystem restoration and flood mitigation by decreasing water velocity, filtering suspended materials, and retaining sediment.

4.2.2. Engineered Leaky Dams

Wooden Board Dams

Wooden board dams are engineered structures composed of planks or logs, intended to retain water and control its flow [55,117]. These dams may be entirely impermeable or exhibit moderate permeability, facilitating regulated water flow, sediment retention, and the creation of pools [118]. They are generally constructed from resilient hardwoods such as oak or elm for durability or lightweight softwoods including western red cedar for enhanced maneuverability [119]. The constructions frequently utilize interlocking planks or logs, reinforced by supports embedded in the riverbed to guarantee stability and resistance to water pressure.

Wooden board dams are categorized into two primary groups according to their construction. Crib dams comprise interconnecting timber cribs filled with rocks and soil, forming a robust structure capable of enduring substantial water pressure [129]. On the other hand, plank dams consist of horizontal wooden boards attached to the riverbed, offering enhanced adaptability in design and construction to accommodate particular site constraints [94]. A key benefit of wooden board dams is their reliable hydraulic

performance. Engineers can accurately estimate flow rates and modify the spacing between the boards to attain specified results [130]. These dams typically consist of several layers of boards positioned at different heights and angles, which serve to radiate energy and regulate a consistent water flow [131]. The utilization of treated lumber might markedly prolong the durability of these structures; nevertheless, it is crucial to evaluate the possible environmental repercussions linked to treated materials [132].

Prominent instances of wooden board dams illustrate their adaptability and efficacy in water control. In the Lake District, England, constructed dams with changeable oak slats allow managers to regulate flow rates based on seasonal requirements [133]. These 2.5 m wide structures include three adjustable slots, enabling the precise regulation of water retention year-round [132]. The Vermont River Conservancy established a series of treated pine board dams organized in three layers. Each structure is 4 m in width and features meticulously calculated 10 cm intervals between the boards, efficiently regulating flow rates while facilitating fish passage [134]. These examples illustrate the versatility and efficacy of wooden board dams in meeting various environmental and hydrological demands.

Rock and Boulder Dams

Rock and boulder dams are constructed by utilizing natural stone materials to regulate the flow of water [126]. However, these dams are particularly effective in high-energy environments, where timber structures may be insufficient. Rock and boulder dams ensure that the aesthetics of the landscape are preserved, while their resilience and organic composition make them suitable for long-term use [121].

Rockfill dams and boulder dams are two of the most common engineered dams constructed using stones. Loose rock materials are compacted in phases to create a stable, impenetrable barrier, which is known as a rockfill dam [135]. Modern construction methods incorporate moisture conditioning and compaction to enhance the dam's structural integrity and prevent seepage. Boulder dams, in contrast, employ larger boulders that are strategically positioned to establish a barrier [122]. The bulk and weight of the materials make boulder dams more difficult to construct, but they offer substantial resistance to water pressure [136]. The removal of the Elwha River dams in Washington State is a well-known example of granite dam construction, and the process restored the river's flow, created new habitats, and used carefully arranged rocks to regulate water flow and ensure stability under high pressure [120].

The construction process for these structures involves sophisticated engineering considerations that extend beyond basic material placement. For example, in steep mountain streams, dam design often incorporates stepped configurations that create a series of pools, effectively dissipating energy while maintaining ecological connectivity. Modern construction techniques utilize advanced compaction monitoring systems, including nuclear density gauges and intelligent compaction technology, to ensure optimal material density throughout the structure [135]. Recent innovations have led to the integration of geosynthetic materials within rockfill structures to enhance stability and control seepage patterns. This approach has proven particularly effective in regions with extreme weather conditions [126]. The placement of materials typically follows strict gradation requirements, with larger rocks forming the exterior armor and progressively smaller materials filling the internal spaces.

Boulder dam construction requires precise placement strategies for large stone elements, often weighing several tons each. The arrangement must maximize interlocking while creating desired flow characteristics [122]. Modern projects increasingly utilize computational modeling to optimize boulder placement patterns, resulting in structures that effectively manage high flow conditions while maintaining natural stream

characteristics [137]. The environmental impact of these structures is significant, extending beyond basic flow control. Studies have documented increased aquatic biodiversity near properly designed rock dams, with the structures providing essential spawning and rearing habitats for multiple species [121]. The natural materials also support benthic invertebrate communities, contributing to overall ecosystem health [138]. Maintenance programs focus on regular structural assessment and periodic repositioning of displaced materials, with well-constructed rock dams typically requiring minimal intervention [136]. The success of various restoration projects, including the Elwha River project, has demonstrated how strategic rock placement can facilitate natural river processes while maintaining necessary flow control [120].

4.2.3. Hybrid Leaky Dams

Wood–Rock Hybrid Dams

The construction techniques and design considerations for wood–rock hybrid dams involve sophisticated engineering principles that merge traditional knowledge with modern structural analysis [123]. The wooden components consist of pressure-treated logs or timbers that are strategically positioned to create internal framework structures [109]. These are arranged in crib-like patterns with interlocking joints that enhance structural integrity. The rock elements include both carefully placed large stones for primary stability and smaller aggregate materials for filtration and sealing purposes [139]. The construction of wood–rock hybrid dams typically begin with foundation preparation using geotextile materials to prevent undermining, followed by the precise placement of primary wooden framework elements at 45–60° angles to optimize flow resistance [140]. This is complemented by the strategic positioning of rock fill with specific gradation requirements and the integration of fish passage features when required for ecological connectivity [141]. The performance characteristics of these structures exhibit unique hydraulic behavior due to their composite nature [142]. The wooden elements create controlled pathways for water movement, while the rock components provide mass and stability [143]. These dams can typically handle a flow rate modulation capacity of 0.5–2.5 m³/s, depending on design specifications [142]. The sediment retention efficiency of these dams typically ranges from 60–85%, with a design lifespan of 25–40 years when properly maintained [118]. Most importantly, they demonstrate resilience in withstanding flood events with up to 100-year recurrence intervals.

In the Pacific Northwest, specifically Washington state's Olympic Peninsula, a series of wood–rock hybrid dams have been successfully implemented, ranging from 2–3 m in height and incorporating local cedar logs and basalt rock [144]. They have proven exceptionally effective in managing seasonal flow variations while supporting salmon-spawning habitats. The success of these implementations has led to increased adoption throughout the region. The European continent, particularly in the Black Forest region of Germany, showcases the historical precedent for these structures. Traditional hybrid dams combining spruce timber and granite have been used for centuries in small watershed management [145]. Modern versions incorporate engineered features for improved stability and flow control, with recent monitoring showing that these structures reduce peak flow rates by 30–40% during storm events.

From an economic perspective, wood–rock hybrid dams often present a cost-effective solution compared to conventional alternatives [129]. Construction costs typically run 20–30% lower than concrete structures, with reduced heavy equipment requirements during installation [132]. The ability to use local materials significantly decreases transportation costs, while proper design and maintenance contribute to an extended service life. These structures provide natural water temperature regulation through shading and pooling

effects, create vital microhabitats in wood–water interface zones, enhance groundwater recharge through controlled seepage, and contribute to carbon sequestration through the use of wooden materials. This multifaceted approach to water management demonstrates how traditional materials can be used to address modern environmental challenges while maintaining ecological balance.

Geotextile-Assisted Dams

Geotextile-assisted dams are a novel method that integrates contemporary materials into the design of natural dams [124]. Geotextiles are permeable fabrics utilized in geotechnical engineering, increasing soil stability and drainage while simultaneously performing functions such as filtration, separation, reinforcement, and drainage in dam construction [125,146]. These materials reduce the likelihood of erosion and failure and improve structural stability. Geotextiles are extensively utilized in the construction and restoration of embankment dams, preventing soil particle loss through filtration while allowing water to pass, thereby preserving the dam's integrity [117]. Their inclusion effectively modulates seepage rates, enhances sediment retention, and supports porous dam structures [146]. A study by Markiewicz et al. [147] in the Netherlands highlights the innovative construction of leaky dams using permeable geotextile layers combined with wooden components. These dams effectively filter agricultural debris while maintaining structural integrity, achieving an 80% reduction in suspended solid concentrations. Similarly, the Thames Catchment adopts geotextile-reinforced leakage barriers, which use high-strength fabric layers to prevent eroding and reduce bank erosion in high-energy streams. These barriers, which are 3 m in width, are both visually appealing and functional [148].

Emerging geotextile tube technology is increasingly used in constructing fine-grain tailings barriers and flood protection systems. Filled with slurry or other materials, geotextile tubes create stable structures that enhance overall structural integrity while significantly improving the seismic performance and reliability of tailings dams through critical support and drainage [149]. According to a study by García et al. [150], Phase 1A of the tailings storage system at the Gran Colombia Gold Segovia (GCGS) mining operation in Colombia integrated geotextile tubes to refine tailings management; these tubes replaced traditional construction materials with mining tailings, which resulted in improved storage efficiency and ensured the long-term stability of the containment dam.

4.2.4. Temporary and Movable Leaky Dams

Seasonal Leaky Dams

Seasonal leaky dams are intended for short-term use during high-risk periods, such as seasonal flooding [80]. These structures are installed prior to flooding events and may be altered or evacuated during periods of minimal flow [151]. Their design ensures efficacy during operation while prioritizing ease of installation and removal; thus, the materials and construction methods are chosen to ensure adaptability, stability, and rapid assembly [112]. These dams are usually lightweight, flexible, and can be quickly assembled and disassembled, which allows for effortless transportation and on-site assembly, making them beneficial for emergency flood management, flash floods, or seasonal water conservation [152]. Additionally, seasonal leaky dams promote biodiversity in river ecosystems and sustain diverse aquatic habitats by restoring water level fluctuations [153].

According to Komporn et al. [154], seasonal leaky dams are effective in managing flood risks, as they can be quickly installed during high-risk periods and removed when flood threats subside. The study found that integrating seasonal predictions into flood management strategies, such as using adaptive reservoir operations, can reduce peak river discharge by 20%, helping to mitigate extreme flood events such as the 2011 Thai flood.

Traditional barriers, such as dikes and sluices, can be supplemented by seasonal permeable dams, which can be incorporated into current flood defense systems [155]. Alongside other flood mitigation strategies, the implementation of seasonal permeable dams is likely to expand due to the heightened occurrence of extreme weather events brought about by climate change, as they can adjust to fluctuating conditions [156].

Mobile Leaky Dams

Mobile leaky dams provide a responsive solution for water management, as they are intended to be relocated in response to progressing environmental conditions or management requirements [157]. Built from natural materials, these structures are designed to blend easily into the environment while simultaneously serving their intended purpose. Their capacity to be rapidly assembled, disassembled, and transported makes them optimal for regions with fluctuating water levels [158]. Mobile leaky dams have been effectively implemented in the United Kingdom, including in Dalby Forest, where they capture sediment and mitigate surface discharge into rivers [102]. These structures are becoming increasingly valuable in resolving the challenges posed by extreme weather events as a result of climate change due to their flexibility.

The design of mobile leaky dams is centered on the balance between mobility and durability. This is achieved by incorporating innovative connection systems and lightweight materials to facilitate movement without compromising structural integrity. Mobile leaky dams have been found to be effective in flood protection systems in dynamic environments, such as Essex, UK, where fallen wood is utilized to slow the flow of water and safeguard homes [159]. In a similar study, the River Aire project utilizes aluminum-framed brush panels that can be effortlessly assembled and relocated by two individuals in times of emergency [160]. In the Murray–Darling Basin of Australia, mobile dams constructed from local stone and wire gabions can be relocated using small machinery to accommodate evolving watershed conditions [161].

4.3. Distinction Between Leaky Dams and Traditional Engineered Dams

The primary distinction between traditional dams and leaky dams is their intended function and design strategy. Leaky dams are specifically engineered to enable controlled water passage through and around their structure, while traditional dams are engineered to create substantial water impoundment with minimal seepage [103]. Every aspect of their design, construction, and environmental impact is influenced by this difference. For instance, concrete, earth, or gravel fill barriers are the typical components of traditional dams, which are solid and impermeable as their principal function is to generate hydroelectric power, provide water supply storage, or construct reservoirs [162]. These structures are engineered to withstand substantial hydraulic pressures and typically include engineered spillways to ensure controlled release during high flows [163]. Significant material processing and heavy machinery are frequently necessary during the construction process, which also includes extensive site preparation and foundation work [164]. Conversely, leaky dams are structures that are purposely permeable, allowing water to travel at a slower pace and to be filtered rather than being entirely obstructed [80]. Their design facilitates the natural processes of streams while simultaneously enhancing habitats and mitigating floods. The construction process depends on the arrangement of local materials, such as wood, brush, or scattered stone, to establish multiple flow paths [165].

The environmental consequences of these two methodologies are quite distinct. Traditional dams usually obstruct fish migration, disrupt sediment transport processes, and significantly alter downstream flow regimes, resulting in variations in the quality of downstream water and temperature stratification in reservoirs [166]. The ecosystem is funda-

mentally altered by the creation of artificial fluvial and lacustrine deposits due to the retention of water [167]. However, leaky barriers preserve ecosystem connectivity and generate advantageous modifications to stream processes, such as facilitating the passage of fish, encouraging the diversity of habitats, and preserving the natural sediment transport processes [168]. Furthermore, leaky dams create diverse microhabitats and improve water quality through natural filtration [169].

Traditional dams are infrastructure projects that are generally large in scope, necessitating substantial investment and resulting in substantial reservoirs [170]. Leaky dams are typically smaller in size, operating at a reach level rather than a watershed level. Rather than a single large intervention, their cumulative effects are accomplished through the implementation of multiple structures. When considering the maintenance requirements, mechanical maintenance of gates and valves, periodic significant repairs, and regular structural inspections are all necessary for traditional engineered dams [55,95,117]. They have predetermined lifespans and ultimate dismantling expenses. Comparatively, the maintenance of leaky dams is less complicated, and it frequently involves the removal of debris and the occasional adjustment of the structure [112]. Their maintenance is often possible manually without the need for specialized apparatuses.

Traditional dams are subject to strict regulatory requirements, safety inspections, and operational protocols, whereas leaky dams are subject to less stringent regulatory supervision, although they must still adhere to local permitting requirements and environmental regulations [171,172]. The two methodologies exhibit significant gaps in their risk profiles. The disastrous consequences of traditional dam failure require the implementation of extensive safety measures and emergency planning. The consequences of a leaky dam failure are typically negligible due to its inherent permeability and smaller scale. One of the main applications of leaky dams is their nature-based role in flood management. Since they allow water to filter through natural materials such as logs and branches, they help to slow surface runoff, reducing peak flows during storm events. Apart from this primary application, they also serve several minor applications and processes, such as mitigating soil erosion, promoting the creation and restoration of wetlands, and enhancing groundwater recharge by encouraging water to percolate into the soil.

In contrast, traditional dams have more extensive and resource-intensive functions in supporting urban and rural water supply systems. These are essential for hydroelectric power generation, offering a stable and renewable energy source by harnessing the potential energy of stored water. Traditional dams also support agricultural irrigation, industrial water use, and large-scale flood control, particularly in densely populated or agriculturally intensive regions.

Traditional dams require considerable capital investment, ongoing operational expenses, and eventual decommissioning expenses, whereas leaky dams are generally associated with simpler removal processes, minimal operational expenses, and reduced initial costs [173]. They are accessible to lesser organizations and communities due to their cost-effectiveness. There is also a significant difference in adaptability to altering conditions. Traditional dams are comparatively inflexible once they have been set up, with a limited capacity to adjust to changing environmental conditions or management objectives [174]. Leaky dams can be more easily modified, relocated, or adjusted to enhance performance or address changing conditions based on monitoring results [175]. The relationship with natural processes of engineered dams and leaky dams also possesses identifiable gaps. Traditional dams require engineered solutions on natural systems, governing and modifying them to achieve human objectives [176]. Leaky dams operate in a more cooperative manner with natural processes while preserving essential ecosystem connectivity and enhancing beneficial functions [177]. The complementary roles that these various approaches can play

in water management are further illustrated by those differences. Leaky dams provide a more naturalistic solution to local-scale water management challenges while promoting ecosystem function, despite the fact that traditional dams are still necessary for certain objectives, such as large-scale water supply and hydropower generation.

5. Conclusions

This review has provided a conceptual foundation for understanding leaky dams as nature-based flood mitigation tools, highlighting their evolution, typological diversity, and comparative position relative to traditional engineered infrastructure. It underscores that leaky dams, whether naturally occurring, engineered, hybrid, or movable, offer context-sensitive and ecologically integrated approaches to managing water flow and reducing flood risk, particularly in small to medium-sized catchments. Compared to conventional flood infrastructure, leaky dams present distinct advantages in terms of cost, adaptability, and ecological co-benefits while also presenting specific challenges tied to their scale, material use, and site-specific effectiveness. However, this review is primarily conceptual and qualitative in scope. It does not delve into technical performance assessments, hydrological modeling, structural optimization, or economic valuation, areas that are critical for practical implementation and are addressed in Part II. Furthermore, the variability in site conditions, lack of universal design standards, and limited long-term monitoring data across case studies remain significant limitations in both this review and the wider literature. Future research should focus on developing context-specific decision frameworks to guide the selection and design of leaky dams based on environmental, hydrological, and community parameters. In addition, interdisciplinary studies linking ecological function, flood resilience, and policy implementation are needed to ensure the successful integration into broader watershed management strategies. This paper lays the groundwork for such technical evaluations and policy considerations by establishing the conceptual and historical context within which leaky dams function.

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