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Review

Water Storage in Dry Riverbeds of Arid and Semi-Arid Regions: Overview, Challenges, and Prospects of Sand Dam Technology

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Abstract: Augmenting water availability using water-harvesting structures is of importance in arid and semi-arid regions (ASARs). This paper provides an overview and examines challenges and prospects of the sand dam application in dry riverbeds of ASARs. The technology filters and protects water from contamination and evaporation with low to no maintenance cost. Sand dams improve the socio-economy of the community and help to cope with drought and climate change. However, success depends on the site selection, design, and construction. The ideal site for a sand dam is at a transition between mountains and plains, with no bend, intermediate slope, and impermeable riverbed in a catchment with a slope greater than 2°. The spillway dimensioning considers the flow velocity, sediment properties, and storage target, and the construction is in multi-stages. Recently, the failure of several sand dams because of incorrect siting, evaporation loss, and one-stage construction were reported. Revision of practitioners' manuals by considering catchment scale hydrological and hydrogeological characteristics, spillway height, and sediment transport are recommended. Research shows that protected wells have better water quality than open wells and scoop holes. Therefore, the community should avoid open defecation, pit latrines, tethering of animals, and applying pesticides near the sand dam.

Keywords: sand dam; runoff harvesting; groundwater recharge; arid and semi-arid regions; dry riverbed

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Citation: Yifru, B.A.; Kim, M.-G.; Lee, J.-W.; Kim, I.-H.; Chang, S.-W.; Chung, I.-M. Water Storage in Dry Riverbeds of Arid and Semi-Arid Regions: Overview, Challenges, and Prospects of Sand Dam Technology. *Sustainability* **2021**, *13*, 5905. https://doi.org/10.3390/su13115905

Academic Editors: Vasileios Tzanakakis and Andreas N. Angelakis

Received: 21 April 2021
Accepted: 20 May 2021
Published: 24 May 2021

1. Introduction

Spatiotemporal variability of precipitation and scarcity of surface water bodies are features of arid and semi-arid regions (ASARs), and in these regions, water epitomizes the most precious resource of the socio-economic and political environment [1–4]. For example, Africa, the second-most populated continent, has the smallest fraction of the total water resources in the world [2,3]. In this region, water supply is inadequate both in the urban and rural communities, and the effort to solve this challenge does not show promising progress [5,6]. Recurrent droughts also aggravate water scarcity and food insecurity [3,7,8]. Moreover, both surface and groundwater resources in the ASARs are held to be highly vulnerable to future climate change [3,9–11].

Most of the population in ASARs depend on groundwater and sand beds of ephemeral rivers for domestic supplies, livestock, and small-scale irrigation [2,12–15]. However, groundwater development is costly in some regions because of the borehole construction techniques (inadequate technical capacity and unavailability of the required equipment), the complexity of geology, scarcity of data, and other related problems, even though it has a lower cost compared to the surface water development [2,12]. Arid regions do not get adequate recharge depending on the geological nature and volume and intensity of rainfall [16]. Where the groundwater development is not feasible, the naturally stored water in sandy riverbed serves the community; however, in regions where the storage volume is limited or in case of demand increase, rural communities frequently collect and store surface water for dry period use [15]. Especially in the rural part of ASARs, water harvesting is the most convenient technique to augment freshwater availability [17,18].

Small dams and ponds are commonly used as runoff harvesting solutions. However, surface water reserving techniques face two primary obstacles, evaporation and siltation, which can drastically reduce effective storage capacity and efficiency [19]. Sand dams provide an alternative to open water dams [6,20]. Sand dams are small weirs constructed across intermittent or ephemeral sandy bedded rivers underlain by bedrock or low-permeability layer to capture and store water [21–23]. The sand stores primarily flash flood, are naturally filtered and protected from evaporation, and help to recharge the aquifer in the surrounding area.

This paper provides an overview of the sand dam application, challenges, and prospects in ASARs. The review primarily covers the working principles, application, construction aspects, advantages, and challenges of sand dam technology. The focus is on peer-reviewed journals, theses, and books, but data extraction includes practitioners' manuals and sand dam constructing organizations reports and websites. First, an overview of the relationship between aridity and water stress and the role of sandy bed intermittent and ephemeral rivers are presented. Next, sand dam technology working principles, characteristics, history, site selection criteria, the effect of sand dams on groundwater level, and design and construction practices are reviewed. The socio-economic impact of sand dams is also highlighted. Furthermore, the challenges and research gaps are summarized, followed by prospects of sand dams. A summary of the review and general recommendations are given, as well.

2. Sandy Bed Intermittent and Ephemeral Rivers

River discharge variability and water resources management problems predominantly result from unstable policies, data scarcity, inadequate capacity, and rapid population growth and urbanization; these are the characteristics of most of ASARs of Africa and Asia [5,24]. Moreover, world water resources are distributed following the patchwork of physiographic structures and climate variability [12,25]. For example, in Africa, about 67% of the continent has arid and semi-arid climate conditions [5], and surface water resources occur in limited areas. In this context, water resources have significant socio-economic implications [24,26]. In general, United Nations Children's Emergency Fund (UNICEF) and World Health Organization (WHO) data show that most ASARs have a high to extremely high lack of access to drinking water (Figure 1).

Water scarcity is not only due to the uneven distribution of water resources and spatiotemporal variable rainfall but also untapped runoff, particularly in the absence of perennial rivers, which can supply water in periods of drought [1,30]. The seasonality of river discharge varies universally from river to river and is influenced by the local seasonal variability of precipitation and evaporation, characteristics of surface runoff, groundwater–surface water interaction, and management practices [31]. Rivers flowing only after the occurrence of rain are called ephemeral rivers, and others that go dry or have very low discharge in at least one of the seasons of the year are called intermittent rivers. Ephemeral and intermittent rivers make up a large portion of the world river network and play a vital role in the eco-hydrological system [32–34].

In ASARs, eroded soil with coarse particle size is transported to the river in the rainy season. Over time, the transported sand is deposited in a different part of the river depending on the bed slope and sand particle size, creating a sandy riverbed. The sandy riverbeds store a significant volume of water in the sand and are important sources of water to the local community and their livestock. However, if the groundwater does not supply the rivers, the stored water is lost in short periods and may not meet the demand when the dry period lasts longer [35]. Moreover, natural riverbeds have spatiotemporally varying bed and transported materials and affect water flow and storage [36].

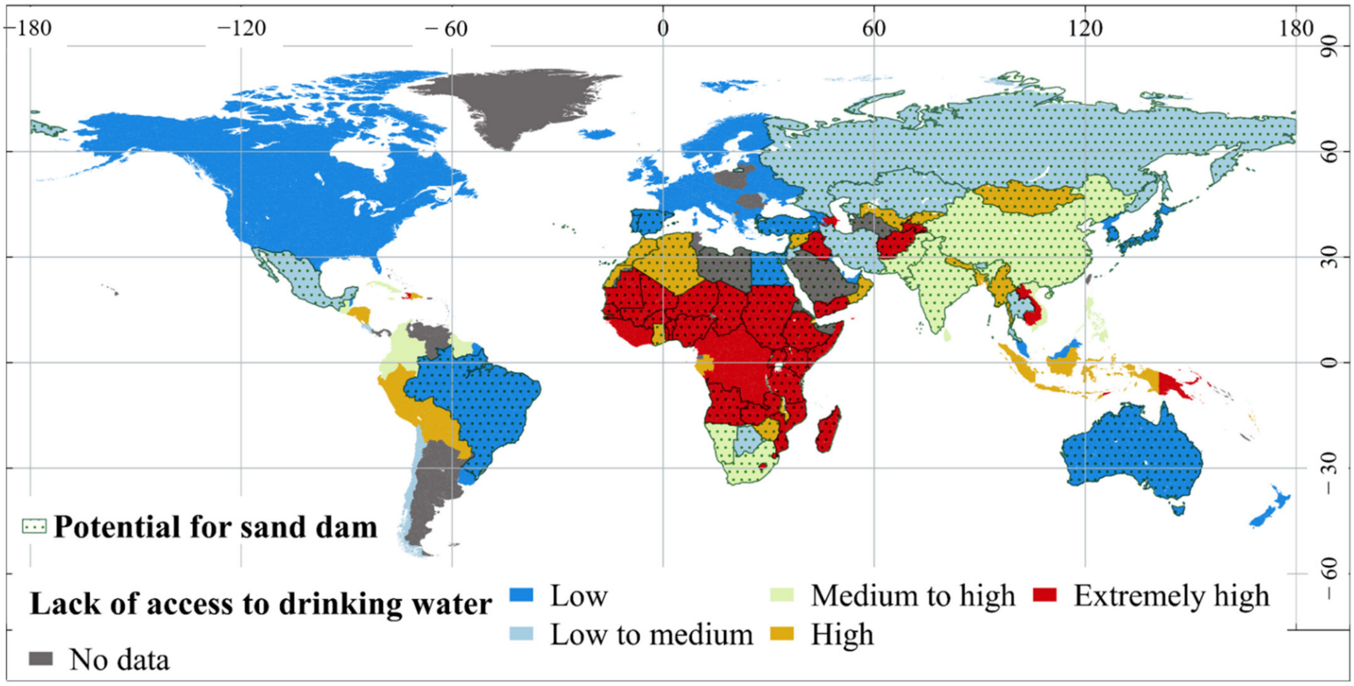

Figure 1. Map showing lack of access to drinking water (low to extremely high) based on UNICEF and WHO data [27] and countries with a potential for sand dam development (collected from reports and websites, particularly from [28,29]).

To augment this water shortage, communities develop water-harvesting techniques such as sand dams in a selected area of the river. Runoff harvesting in sand reservoirs is crucial to solving the major growing problem of reduced groundwater levels, which induces water scarcity in rural areas [37]. Rivers with sandy riverbeds occur mainly in arid and semi-arid climate zones, including America and Australia, and more than 60 countries in ASARs have potential for san dam development (Figure 1). However, the reports of application are dominantly from the eastern and southern parts of Africa and a few countries in Asia such as India (Figure 2).

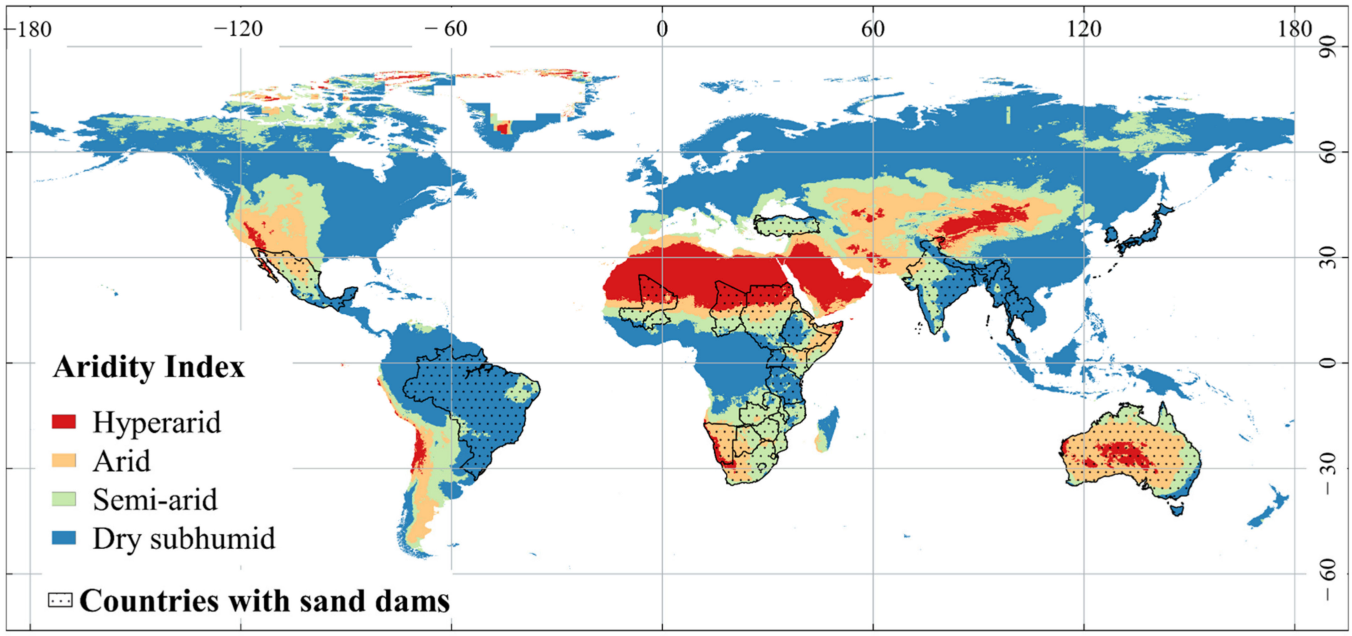

Figure 2. World aridity index [38] and countries with sand dams, collected and modified from [29,39] and Managed Aquifer Recharge Portal [40].

3. Sand Dam Technology

Runoff harvesting practices to augment freshwater availability have been applied in dry areas for centuries, including in Roman times [1,17,39]. Sand dams, alternatively called trap dams, sand storage dams, sponge dams, or desert water tanks [39,41,42], are one of the popular runoff harvesting techniques. Even though the application of sand dams in ancient civilization is not documented separately from other subsurface storage systems, sand dams have been constructed and used for millennia in ASARs of Africa, North and South America, Asia, and the Middle East [18,25,43,44]. The technology has also been applied in Europe [39,45].

More recently, sand dam technology has been widely applied in Africa, specifically in Kenya and Ethiopia; the majority of them were built after the 1990s. Since 1960, Kenya has built over 1500 sand dams [7]. Kenya is the leading country in the application of sand dams; more than half of the sand dams in the world are located in Kenya [46]. In 1973, sand dams were used to develop water resources in arid regions of the United States [23].

A sand dam has several advantages over open water storage. The sand filters and protects the water from evaporation and contamination, and it has a lower risk of creating a preferable environment for disease-carrying mosquitos. Storing water for later use using sand dam technology improves water quality and availability, supports biodiversity, is cost-efficient, and enjoys simplicity of construction [47,48]. Sand dams also serve road crossings in rural areas of Africa [29]. In some areas, the cost of a sand dam is much less than a water borehole [49]. Because of minimal maintenance and long life, sand dams frequently retain their effectiveness for many decades up to a century [39]. However, their efficiency relies on several and complex biophysical and technical factors, including design efficiency, construction methods, topographic and geological features of the surrounding area, climate variability, and management [7,21]. In this section, the basic working principles (sand dam hydrology), sedimentation, site selection, design, construction, and the effect of sand dams on groundwater levels are highlighted. Table 1 provides the principal areas of the literature survey, data collection, and sources.

Table 1. Synopsis on key sand dam studies used as a data source for this study and the role players of sand dam construction (organizations).

Study Focus, Site	Source, Reference
Assessment of water quality	[50–52]
Effect of a sand dam on groundwater	[21,47,48,53,54]
Climate change and drought	[20,55,56]
Particle size distribution and evaporation	[57]
Occurrence of a sand dam	[29,40]
Working principles and water balance	[19,58–60]
Sustainable development analysis	[18,49,61]
Functionality assessment	[62]
Site selection, feasibility studies, manual	[22,46,63–67]
African Sand Dam Foundation	[68]
Excellent Development	[28,67]

3.1. Sand Dam Hydrology and Working Principles

Sand dams are commonly built in ASARs with infrequent high-intensity rainfall and impound water in sediments deposited in the upstream area [7,21,39]. The dam is built in such a way to create a small reservoir, which is characterized by an increasing cross-sectional flow area and decreasing flow velocity or turbulence. The turbulence provides a sufficient force for keeping fine particles in suspension, and at the same time, the reduction in turbulence allows coarse sediment to drop out of the flow, often resulting in the formation of a delta at the upstream end of the backwater. Meanwhile, lighter particles that remain in suspension at the top of the backwater are deposited closer to the dam wall, where velocities and turbulence continue to fall, or they remain in suspension and flow over the top of the structure. The deposited sand particle creates an artificial aquifer and acts as a sponge that retains water for dry period use. The storage replenished in each rainy season.

The water stored in a sand dam can be extracted via various approaches. Traditionally, water is often extracted using scoop holes. Higher-cost, protected sources may also be used, such as large diameter wells or piped distribution systems passing through the dam wall, hydraulically connected to the aquifer by an infiltration gallery [13,23]. The water can be used for drinking, domestic uses, livestock watering, wild animal watering, and irrigation [25,69,70].

Understanding the hydrology of sand dam requires investigation of the hydrological processes near the storage area and the total catchment area, and it is important for the successful development of the system [60]. The basic hydrological processes, working principles, and sand dam components are presented in Figure 3.

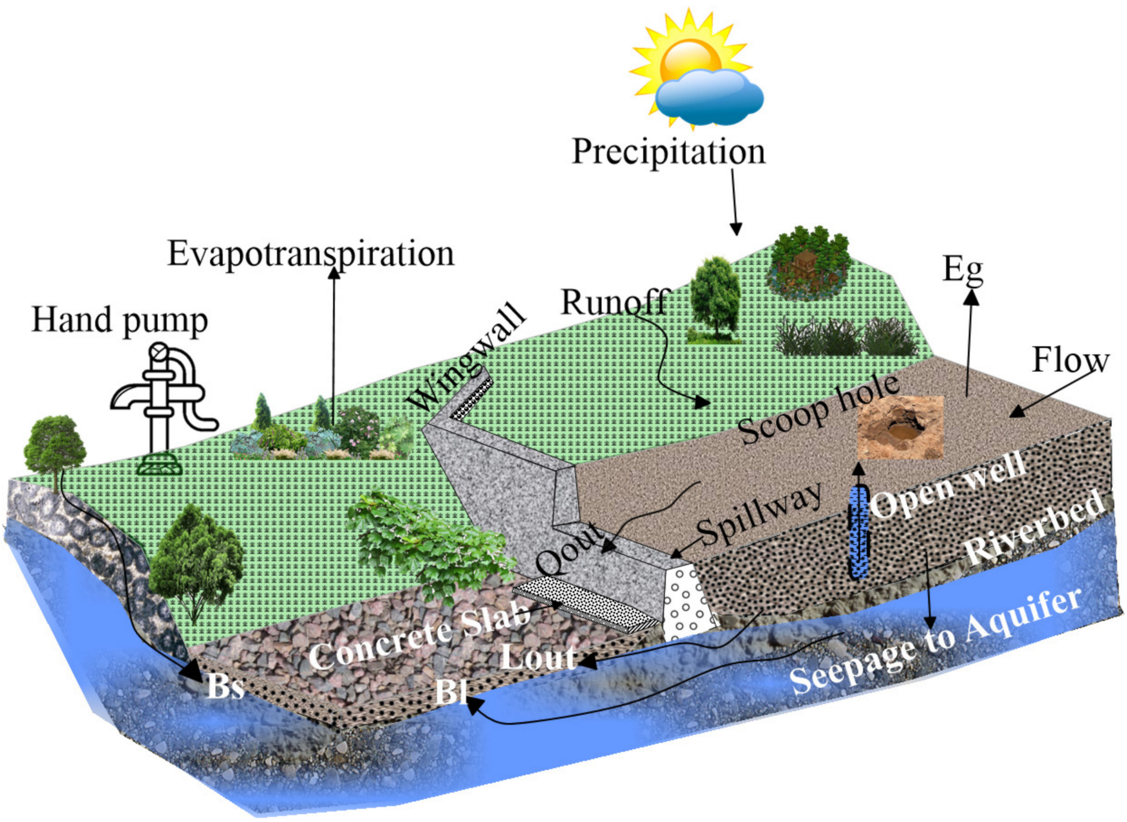

Figure 3. Main hydrological processes, components of a sand dam, and working principles of a sand dam [47,58], with moderate modifications. Lout, leakage through the base and body of the dam; Bl, baseflow; Eg, evaporation from sand; Qout, spillway discharge; Bs, lateral baseflow.

3.2. Sedimentation

The transported and deposited sand type and grain size are key factors in determining the amount of water collected and the yield of the reservoir [1,39]. The rainfall intensity and source of the sediment determine the size and type of sediment particles. The primary sources of sediment are riverbed and riverbank erosion. However, in ASARs, which have less vegetation cover, the surface runoff-generated sediment also contributes significantly to the sediment load in the river. The particle size dramatically affects a dam's ability to store and transmit water, and to protect evaporation loss and water yield [71]. The storage capacity increases when coarser sediment is deposited [23]. Flood flow infiltrates faster, and groundwater flows to or from the artificial aquifer faster through larger grain size [1]. Moreover, when the grain size of the riverbed deposition is coarser, water can be abstracted more easily from wells in the riverbed aquifer. Nevertheless, sediment with very high permeability may limit the duration of water availability during the dry season, especially when dams with small storage volumes are constructed on rivers with little baseflow. If subsurface baseflow quickly drains from upstream reaches and enters the reservoir, some will likely be discharged and lost before it is used. By contrast, less permeable sediments restrict upstream flow, providing slower recharge throughout the dry season as water is gradually abstracted.

The volume of sediment stored upstream of the sand dam can be approximated using the following relationship [22,67]:

$$V_s = \frac{D_s \times W_{rc} \times L_s}{3} \quad (1)$$

where V_s is volume of sand at upstream of the dam (L^3), D_s is the maximum depth of sand storage (L), W_{rc} is the maximum width of river channel (L), and L_s is the length of sand storage (L). Thus, from Equation (1), the effective water storage capacity is estimated using the following relationship (Equation (2)) [22]:

$$V_w = V_s \times n_e \quad (2)$$

where V_w is extractable stored water in the sand (L^3), V_s is sediment volume (L^3), and n_e is effective porosity (percentage of drainable porosity as given in column four of Table 2).

Table 2. Extractable volume of water based on particle size and saturation [22,72].

Soil Type	Range Grain Size (mm)	Porosity (%)	Effective Porosity (%)
Silt	<0.5	38	5
Fine sand	0.5–1	40	19
Medium sand	1–1.5	41	25
Coarse sand	1–5	45	35
Small gravel	5–19	46	41
Large gravel	9–70	51	50

The deposition of silt reduces the porosity of the storage material, adversely affects the sand dam's performance, and thus, sand dam design and construction are based on the principle of washing down finer particles [55,58]. At the same time, the sand dam should accumulate both fine and coarse sand particles. Coarse sediment is more important near the bottom of the reservoir to allow drainage while fine particles are more acceptable near the surface [71]. Assuming that a sand dam aquifer is of sufficient depth to store adequate water below the depth of evaporative influence, finer sediment may be more permissible near the surface, but for relatively shallow aquifers, coarse sediment is desirable at all depths to limit evaporative losses [71]. The accumulated sand dam may be filled with water up to 35–40% of its volume [56,73], but there is no consensus on the particle size and distribution [71].

Climate governs the relationship between mechanical and chemical weathering and significantly influences the properties of sediment—a lower rate of chemical weathering in arid climates may produce more coarse-grained sediments. Regardless of their source, the most favorable parent rocks are coarse granite, quartzite, and sandstone, while basalts and rhyolites tend to produce less favorable sediment for the sand dam [39].

3.3. Sand Dam Site Selection

A successful project design entails a detailed preliminary analysis, and recently, in large-scale site selection, a combination of remote sensing and Geographic Information System is playing an important role [63]. The location of flow barrier structures affects the functionality in almost every dimension including, storage capacity, sedimentation, construction difficulty, service life, economy, and the environmental response [7,21]. The siting principle is almost similar to surface water dams and needs a comprehensive understanding of hydrological and geological features of the catchment area, project cost, demand assessment, environmental responses, topography, geotechnical suitability, the gradient of the riverbed, texture of sand, floor under the sand, height of the riverbanks, and accessibility of construction materials [21].

The topographical suitability of an area is evaluated for mainly acceptable relation between storage volume and dam height, evaporation losses, and sediment transport. To minimize evaporation losses, therefore, a sand dam should ideally be in a well-defined gully or riverbed between steep rock banks. While in mountainous areas with very high gradients, it may be difficult to find an acceptable relation between storage volume and dam height in less mountainous regions, sand dams will tend to fill wider and shallower basins that can cause higher evaporation loss. Particle sizes in a riverbed strongly correlate with those on the riverbanks, and a catchment with a slope greater than 2° is a strong predictor of sandy riverbeds [74]. Riverbed particle sizes are also proportional to channel slope, as coarse particles found in steep mountain catchments transition to fine silts in lower-lying floodplains. Due to the inverse relationship between particle size and potential dam storage volume along the length of a river siting, siting sand dams in transitional zones between mountains and plains, where intermediate slopes permit the transport of coarse material while allowing for sufficient storage volume, is recommended [71].

Traditionally, people use trees, which show the water availability in a shallow depth, to select an appropriate section of the river for a sand dam. Location of waterholes, hand-dug wells, types of rocks and boulders, and the coarseness of sediments also provide valuable information for the selection of suitable riverbed sections. The riverbed in which water is to be stored may be underlain by bedrock or unconsolidated formations with as much as low permeability and no bend. The impermeable layer should be closest to the riverbed surface.

Sand dams are preferably located in geological environments where weathering produces enough sand and gravel, and thus, studying the geological features of the catchment area of a sand dam is necessary for predicting the type and characteristics of the expected sediments. It is important to avoid areas with calcrete, a salty whitish substance that turns water saline [75]. Moreover, the geotechnical material underlying the site of a sand dam needs to be feasible and meet the design standards for ensuring the stable construction of the dam wall. If anchoring is executed using a concrete foundation on the rock surface, it minimizes seepage below the dam [39]. In Table 3, a summary of the main site selection criteria and indicators of ideal sand dam site are presented.

Table 3. Summary of site selection criteria and key indicators of the feasible location of sand dam construction.

Parameter	Value	Reference
Catchment slope	>2°	[74]
Catchment size	0.15–366 Km^2	[71,74]
Riverbed slope	0.2–5%	[46,48,65]
Width of riverbed	5–25 m	[65,76]
Riverbed thickness	0.8–2.5 m	[76]
Particle size in the bed	>0.2 mm	[65]
Precipitation	>200 mm/year	[46]
Water indicating plant occurrence, at least two types	<10 m radius	[22,46]
Stream order [77] *	1–3	[46]
Minimum flow rate for sediment transport	0.2 m/s	[65]

* If the stream order has numbers up to seven, most successful sand dams are on 1–3 [46].

The incorrect siting includes selecting a catchment area that cannot produce coarse sand but produces a large volume of fine sand, fractures, or permeable layers, which can cause large seepage losses. Therefore, to meet all the required demands, a proper site selection is one of the most important factors for the success of sand dam technology [46].

A wrong siting procedure may cause seepage of the water stored in the sand through sedimentary rocks, boulders, and fractured features [16].

3.4. Design, Construction, Maintenance, and Management

Besides improper siting, sand dam failures have been blamed on poor construction procedures [46]. Elements of sand dam design include proportioning of the components, e.g., wing wall, spillway, downstream protection, and the main dam body, and it is the most important aspect of the entire system [69]. Particularly the spillway design is one of the key factors for the success of sand dams [7,22,48,75,78]. The principle is to build a fraction of the total height that allows a sufficiently high flow velocity at a time so that fine particles are washed out from the reservoir while the coarse particles settle. The limit of each stage is set by estimating the sedimentation process in the storage area, from the extent of natural sedimentation in the river, or calculations of water velocities in the reservoir. One-stage high spillway may show lower robustness to the inherent variability of precipitation, river discharge, and sediment transport.

Problems with the construction of one-stage high spillways and the height of stages are the leading factors for the failure of a sand dam [7]. During the feasibility study and planning of the construction of a sand dam, however, the material is waiting to be transported to the dam site from the catchment by a flood of unknown intensity in the next rainy season. This makes the efficient design of a sand dam a complicated task that needs further hydrological and hydraulic investigations [39].

Sand dams are built using locally available materials, including stone, concrete, stone masonry, gabion with clay core, gabion with clay cover, and stone-fill concrete [23,55]. However, most sand dams are concrete structures between 10 and 100 m wide and 1 to 6 m high [49,55,79]. Regardless of type, sand dams are built to allow over-topping by floods but watertight and founded on an unweathered solid rock to prevent a structural failure of the dam wall [39]. A sand dam has to be well protected against erosion both along the banks and at the dam toe [39].

The cost of a sand dam has a large range and has increased over time [7,17,56]. A sand dam may need low to no cost of maintenance and repair and can sustain hundreds of years [80]. However, regular maintenance of pumping wells and/or other water abstraction systems is required. The community should check the dam site for erosion after each flood event and avoid open defecation, pit latrines, tethering of animals, clothes washing, and use of pesticides/chemicals upstream of the sand dam. The common properties of sand dams are highlighted in Table 4.

Table 4. Key characteristics of sand dams and recommended or common practices.

Characteristics	Range	Reference
Height of sand dam	1–6 m	[49,55,79]
Width of sand dam	<40 m	[46]
Construction stages	18–50 cm	[7,7,22,22,71,71]
Spillway height above sand level	<50 cm	[22]
Effective storage volume	25–40%	[50,67,72]
Construction cost (USD)	5000–20,000	[46,67]
Retained river flow	1–3%	[18,80]
Distance between series of sand dams	>500 m	[18]

3.5. Effect on Groundwater

Researches show that the seepage from the riverbed and recharge of the riverbanks causes a rise in the groundwater level in the nearby aquifer [48,53]. The extent of a sand dam's effect on the groundwater level, however, is determined by the geologic nature and the water abstraction rate from the sand storage and the natural aquifer in the riparian zone [48,60]. The presence of the sand dam influences the natural aquifer in the area; the groundwater level increases, particularly upstream of the dam [54]. The groundwater also affects the sand dam storage [81].

4. Socio-Economic Impacts of a Sand Dam

Water scarcity and lack of improved drinking water affect the overall socio-economic activities of a community. In rural parts of Africa, it is common for people, mainly women and children, to travel more than 3 h to get water [49]. In this regard, compared to the no sand dam cases, the impact of a sand dam is significant—it encourages permanent settlement of the community, increases food production, and improves ecological health [25,78]. Moreover, a sand dam's long life, low or no maintenance cost, and high level of community involvement often contribute to the structure's value in low-resource contexts. Fundamental socio-economic impacts of sand dams can be summarized as follows:

1. Saves 30–90 min spent on collecting water [25,67];
2. Improves the vegetation cover in the area, supply of water for livestock, wildlife, and small-scale irrigation and increases food production and income [25,49,67,80];
3. The sand filters water and reduces pollution, lowering water-related health risks [43];
4. Gender empowerment—saving time and energy for women and children from traveling to get water so they can, e.g., attend school [67].

Community members are frequently involved in almost every step of the process, often by navigating land use issues, lending local knowledge to the siting process, and making decisions about abstraction methods and other aspects of sand dam development [78]. The participation of the community in sharing costs and responsibility has proven effective in developing local ownership, which is closely linked to the sustainability of water supply projects [82].

5. Challenges of Sand Dam Application

Even though most reports show the success of sand dam technology, a large portion of the constructed sand dams are not functioning as intended [21,50]. Africa is home to over 3000 sand dams, yet about 50% of the sand dams are nonfunctioning [21,61,71]. About 90% of sand dams built from 1970 onwards have failed, mainly due to sedimentation problems, and a large number of sand dams have storage problems [22,71].

The failures can be seen in either or in combination of low to no coarse sand material storage, none or low water yield, and low cost-efficiency values [7]. The principal reasons for the poor performance of sand dams are incorrect siting procedures and inefficient design problems. Studies on water quality assessments show scoop holes and open water wells/unprotected wells have water quality problems.

5.1. Water Quality

Protection of water from pollution is one of the main strengths of sand dam technology [23,43]. Although theoretically, sand filters water effectively and the water from the sand dam is clean, there are several quality concerns [43,52]. The presence of health treating coliforms and a high concentration of salt is among the common problems [52]. Values of turbidity and conductivity exceed WHO standards [50]. Particularly in sand dams where the water abstraction system is using scoop holes and hand-dug wells, the problems are high due to the exposure to contaminants from animal manure and decay of dead plants [52,83]. The defecation and urination by the animals within the river may lead to the build-up of dissolved solids, nutrients, and possibly fecal coliform bacteria [83].

Kitheka [83] evaluated the effect of water exchange between the nearby aquifer, including bank storage and water stored using a sand dam. The author found that high total dissolved solids (TDS) concentrations flow from the banks and aquifer to the sand dam that leads to relatively high salinity and conductivity. Moreover, in the dry season, the TDS and salinity in sand dams and wells are much greater than that in the river sand due to entrapment and more dissolution of rock minerals; evapotranspiration may also increase the concentration of dissolved mineral salts.

Table 5 highlights the common water quality parameters from the three most recent studies on water quality. The authors evaluated the parameters with the percentage of compliance with WHO standards [84] from the collected and tested samples. The number of samples and case studies are different in each study. The parameters that are given only in range values are presented here.

Table 5. Common water quality indicators and compliance percentage with WHO standard or measured ranges from sand dam water [50–52]. Percentage values show the compliance of analyzed water quality parameters with WHO standard, SC = scoop hole, W = well.

Parameter	Scheme	[51]	[50]	[52]
Escherichia coli	SC	46%	-	<10,500 mg/L
	W	80%	-	<10,200 mg/L
Total coliforms	SC	4%	11%	14%
	W	53%	70%	<10,000 mg/L
Total dissolved solids (TDS)	SC	64–872 mg/L	-	<3500 mg/L
	W	692–1132 mg/L	-	<2500 mg/L
Turbidity	SC	0	8%	-
	W	67%	41%	-
pH	SC	100%	100%	-
	W	100%	100%	-
Electrical Conductivity	SC	-	77%	-
	W	-	74%	-

5.2. Evaporation and Seepage Losses

In Kenya, some sand dams are found to lose up to 80% of the stored water [7,21]. Evaporation and seepage are the leading causes of water loss [7,60]. The effective storage capacity of a sand dam is a combination of collected sand volume, evaporation, and seepage [7].

The sand reduces evaporation losses, especially when the water level goes down from the surface—about 8% less water evaporates from the surface of saturated sand compared to open water surfaces [57,85]. Evaporation effectively ceases for water stored 60–90 cm below the surface of a sand bed [57,85,86]; however, it depends on the particle size [16,57,85,87]. This is important in ASARs where evaporation significantly exceeds other hydrological components [30]. However, the accumulation of undesired sand types and sizes affects this result. Hence, shallow depth of sand may not only have limited storage volume and yield but a higher vulnerability to evaporation loss. Especially resilient sand dams are those with greater depth of sand sediments [7]. Given the variation in community goals and the range of acceptable performances, it is difficult to define a single objective in terms of the particle size distribution of trapped sediment.

Seepage has positive downstream effects, such as groundwater recharge; however, it is considered a loss for water harvesting structures [17]. Seepage may lead to low yield and supply capacity [7,60]. About 5% of the total water yield can be lost by seepage [20,61]. To store water for a longer time using a sand dam, the riverbed needs to be fairly impermeable [60]. Rock outcrops on the surface of the riverbed and/or across the thickness of the riverbed have a high potential to seepage water. There are also chances where the sand reservoir gains water from the nearby aquifer [60,83].

5.3. Downstream Effect

The working principle of the sand dam is on 1–4% of the river flow retaining principle, and so far, there have been no reports on the effect of the sand dam on the downstream area [17,48,55,60]. However, Aerts et al. [55] pointed out that in the future related to climate change, this percentage increases significantly and affects the downstream environment negatively. There is a possible reducing effect on the downstream area when networks of sand dams are constructed [48]. Therefore, future studies need to consider a network of dams and climate change to assess the possible downstream effect of a sand dam.

5.4. Storage Capacity and Cost-Efficiency

Estimating the volume of water that can be stored behind a sand dam is challenging for practitioners, as there is no proven applicable formula [49]. There is also a lack of cost-efficiency reports of the constructed sand dams [7,17]. Recent studies, for example [46], are showing that a large number of sand dams fail to provide water in dry periods. A physical survey performed on 30 sand dams in Kenya by de Trincheria et al. [7] focused on the depth of accumulated sand, sand particle texture, specific yield, and slope of riverbed, showing that both the performance and cost-efficiency of the sand dams are very low. The authors also point out that this study output can be representative of sand dams in other parts of the country. Water harvesting using a sand dam is costly compared to other techniques [17], and therefore even though it is usually considered simple technology, it is challenging for communities to efficiently develop sand dams without technical and economic help [18,48].

Siltation affects 40–60% of sand dams [61], and the spillway height and one-stage construction are mentioned as one of the causes of siltation [7], but the multistage construction takes time and makes the sand dam more costly. Most of the sand dams studied in southeastern Kenya lose up to 50% of their water due to the shallowness of accumulated sand [7]. Despite its reliability in terms of availability, quantity is insufficient for inhabitants and fails to support macroinvertebrates [21].

6. Research Gaps

The majority of the studies performed on sand dams focus on hydrology, working principles, and water quality, but in-depth investigations can be grouped into eight (Figure 4). More than 50% of the works are on water balance and general aspects, which touch on working principles, science, and experiences. Interestingly, from the limited number of published studies, the contribution of student papers is high. The publication rate also increased significantly in the past 3 years (Figure 4b).

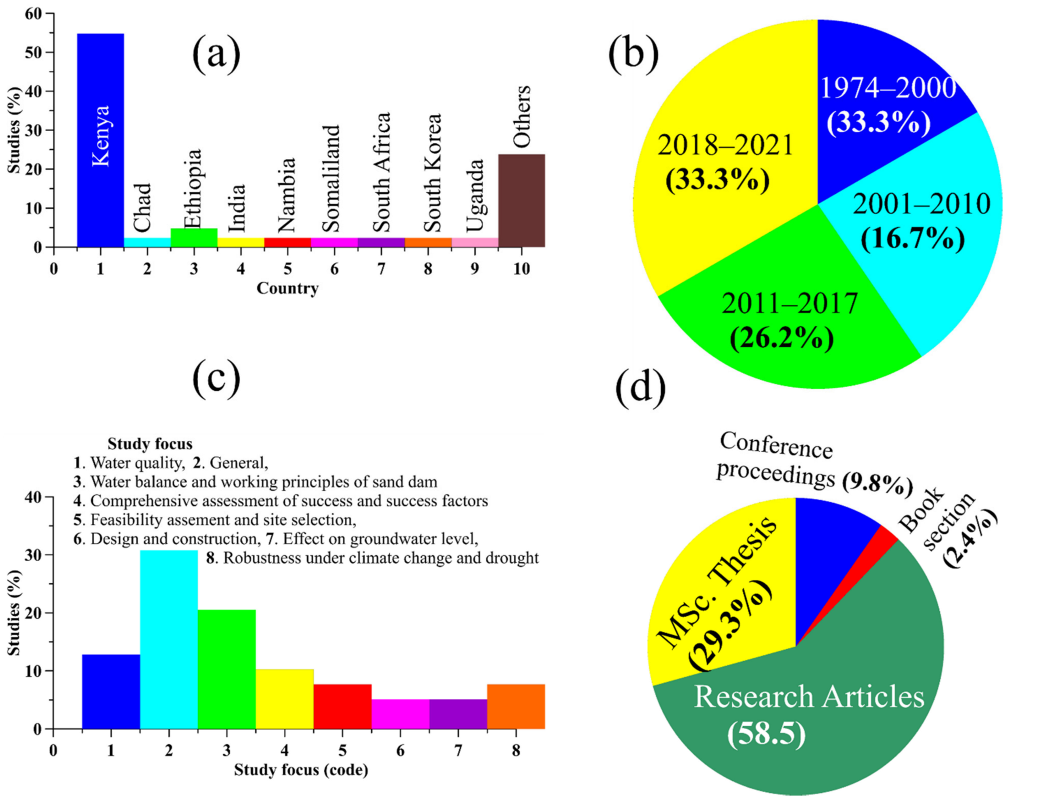

Figure 4. Statistics of available case studies based on the study region (**a**), year of publication (**b**), study focus (**c**), and type of publication (**d**).

6.1. Field Data and Case Studies

Contextually, despite the important role played by ephemeral rivers on hydrological systems, few or no studies have been undertaken to unravel their hydrologic and water quality characteristics. In ASAR, there is a scarcity of data and information on the variation of salinity in sandy rivers. Due to these and related problems, even though the sand dam is an old water harvesting technology, available recorded data are scarce [60]. In sand dam technology development, data and studies on hydrogeology characteristics and rainfall variability are rarely available [55]. Knowledge of the hydrological data is important for estimating the total river flow, sedimentation process, structural design of the dam, etc., but since sand dams are most often built on small rivers with relatively limited regional significance, the availability of long-time recorded data is limited [48]. Because of this, most studies regarding sediment transport and sand dam hydrology are restricted to one or just a few highly monitored sites and a single rainy season.

The successful application of sand dams is site-specific and the contribution of success stories, failures, and limitations could help to maximize the benefits of sand dam and revise the practitioners' manual. However, to date, almost all studies, particularly the research articles, are from a few countries (Figure 4). From the total publications, most of the studies are primarily from East Africa [25]. Moreover, the numbers of sand dams constructed globally are not known, and the occurrence is not documented well [46]. Well-documented data of sand dams such as the recently developed Managed Aquifer Recharge Portal [40] would help researchers to access the information. The Managed Aquifer Recharge Portal tries to include sand dams, but only two dams are available on the website.

6.2. Studies on Long Term Catchment-Scale Hydrological Processes

Even though the ideal sand dam location is described based on the general geometrical storage capacity, slope stability, and geomorphology of the river, the characteristics of the sand dam catchment area regarding the sediment transport and hydrological processes are not addressed. A few researchers, e.g., [47,48], reported the effect of sand dams on groundwater investigations, but the spatial variability in the local geology and its interactions with groundwater near the sand dam is not reported. Kitheka [83] studied bank storage and the sand riverbed water quality and found an important implication for further studies on groundwater–surface water interaction in the sand dam area. The water quality assessments related to the groundwater–surface water interaction, upstream–downstream environmental and hydrological differences, and catchment-scale sediment and other contaminant transport studies are needed. Future studies should investigate water quality in the sand dams towards evaluating the salinity increase because of high rates of evapotranspiration [21].

It is not clear how different parameters contribute to the poor performance of sand dams, mostly because of a lack of information on how hydrological processes around sand storage dams function [48]. Several researchers suggested alternative spillway design options [61]; however, there is no consensus on the design that can reduce siltation. Despite several sand dams' failure to serve their intended purpose, most practitioners' manuals do not have any maintenance suggestions, and even the most recent studies do not address this issue.

7. Prospects

Rivers in several parts of the world are currently showing and are further projected to show decreased flow under future climate change scenarios [88]. The low flow is projected to drop considerably [89,90], and it may exacerbate freshwater availability problems. The water-stressed population will be more vulnerable to water scarcity [4,73]; in Africa, water resources including groundwater will be affected [91]. Runoff harvesting practices help to improve water availability for domestic and agricultural use in ASAR [17,30]. Small water conservation techniques have the potential to cope with this water stress caused by potential climate change and drought; the sand dam is one of these techniques [20,55,56,80].

The application of sand dams shows an increase in water conservation, especially in eastern Africa.

Currently, sand dams are constructed by different non-governmental organizations in collaboration with the community [18]. An organization called Excellent Development has an objective to support other organizations and construct more sand dams, ideally up to one million sand dams by 2040 [28]. More recently, governments are also taking the responsibility to build sand dams.

Reports show that an operational sand dam has the potential to raise the economic status of the community dwelling near the dam [56] even though the cost–benefit analysis reports are scarce. With the promising water productivity in some sand dams [25], small irrigation practices may expand and support the community in developing countries.

8. Summary and Recommendations

Intermittent and ephemeral rivers make up much of the world river network and play an important role in the eco-hydrological system. The sandy riverbed of these rivers serves as natural water storage in ASARs. If the natural water storage in the riverbed cannot meet the water supply demand in the area, the community augments freshwater availability by using runoff-harvesting technologies. This paper gives an overview of sand dam applications, challenges, and prospects. Sand dam technology has a long history in augmenting freshwater availability in dry seasons for domestic and agricultural uses in ASARs. The technology has the potential to cope with future stresses posed by climate change.

The performance of sand dams depends on site selection, construction, design, and water abstraction techniques. The site selection is based on geological, hydrological, hydrogeological, and topographical characteristics of the catchment area and the riverbed, along with the availability of construction materials and accessibility to the community. Accumulation of both coarse and fine sand particles is required to maximize the storage and ease of water abstraction while preventing excessive evaporation loss. Availability and transportation of the required sand particles rely on the rainfall intensity, flow velocity, and source rock. Therefore, a catchment with a slope greater than 2°, annual rainfall greater than 200 mm, and rich with coarse granite, quartzite, and sandstone is the most favorable site for a sand dam. The river section should also have low permeability of the riverbed, no bend, intermediate slope, and well-defined riverbanks in the transition zone of the mountains and the plains. Multi-stage spillway design and construction are needed to avoid siltation.

While the research outputs on the sand dam are increasing dynamic, particularly for the past three years, most of the studies on hydrology are focused on water quality, working principles, robustness to climate change, and environmental response. In addition, most of the studies are only from East Africa. Integrated hydrogeology, groundwater–surface water interaction, and environmental response studies in the catchment and nearby areas are required. Studies from Kenya show that most sand dams failed both in storage and water quality. The core causes for the failures are siltation resulting from one-stage spillway construction, evaporation loss, low-quality parent rock, and pollution of open wells and scoop holes. Revision of practitioners' manuals—based on further experiment on the dimensioning and construction of the spillway, sedimentation, storage volume, seepage loss, and evaporation loss—is recommended. To prevent water pollution, the community should protect the dam area from erosion and avoid open defecation, pit latrines, tethering of animals, and application of chemicals in the surrounding areas.

Author Contributions: Conceptualization, B.A.Y. and I.-M.C.; writing—original draft preparation, B.A.Y.; writing—review and editing, B.A.Y. and I.-M.C.; resources and data curation, J.-W.L. and M.-G.K.; visualization, M.-G.K. and I.-H.K.; supervision, I.-M.C. and S.-W.C.; funding acquisition, I.-M.C. and S.-W.C. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Korea Ministry of Environment (MOE) as a Demand Responsive Water Supply Service Program (146515).

Conflicts of Interest: The authors declare no conflict of interest.

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