Sand Dam Technology

Subjects: Water Resources
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Sand dam 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

1. Introduction

Runoff harvesting practices to augment freshwater availability have been applied in dry areas for centuries [1][2][3]. Sand dams, alternatively called trap dams, sand storage dams, sponge dams, or desert water tanks [3][4][5], are some 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 [6][7][8][9]. The technology has also been applied in Europe [3][10].

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 [11]. 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 [12]. In 1973, sand dams were used to develop water resources in arid regions of the United States [13].

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 [14][15]. Sand dams also serve road crossings in rural areas of Africa [16]. In some areas, the cost of a sand dam is much less than a water borehole [17]. Because of minimal maintenance and long life, sand dams frequently retain their effectiveness for many decades up to a century [3]. 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 [11][18]. 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	[19][20][21]
Effect of a sand dam on groundwater	[18][14][15][22][23]
Climate change and drought	[24][25][26]

Study Focus, Site	Source, Reference
Particle size distribution and evaporation	[27]
Occurrence of a sand dam	[16][28]
Working principles and water balance	[29][30][31][32]
Sustainable development analysis	[6][17][33]
Functionality assessment	[34]
Site selection, feasibility studies, manual	[35][12][36][37][38][39][40]
African Sand Dam Foundation	[41]
Excellent Development	[42][40]

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 [11][18][3]. 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 [43][13]. The water can be used for drinking, domestic uses, livestock watering, wild animal watering, and irrigation [7][44][45].

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 [32]. The basic hydrological processes, working principles, and sand dam components are presented in Figure 1.

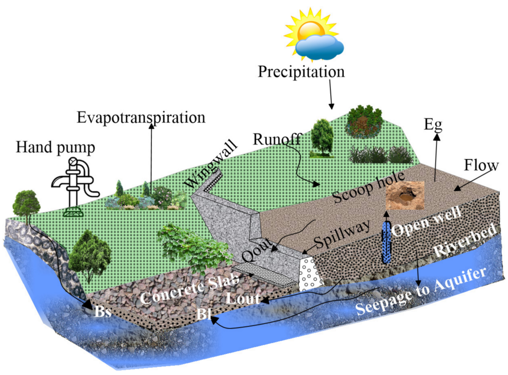

Figure 1. Main hydrological processes, components of a sand dam, and working principles of a sand dam [14][30], with moderate modifications. Lout, leakage through the base and body of the dam; Bl, baseflow; Eg, evaporation from sand; Qout, spillway discharge; Bs, lateral baseflow.

2. 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 [18][19]. Africa is home to over 3000 sand dams, yet about 50% of the sand dams are nonfunctioning [18][33][46]. 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 [35][46].

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 [11]. 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.

2.1. Water Quality

Protection of water from pollution is one of the main strengths of sand dam technology [13][8]. Although theoretically, sand filters water effectively and the water from the sand dam is clean, there are several quality concerns [8][21]. The presence of health treating coliforms and a high concentration of salt is among the common problems [21]. Values of turbidity and conductivity exceed WHO standards [19]. 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 [21][47]. 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 [47].

Kitheka [47] 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 2 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 [48] 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 2. Common water quality indicators and compliance percentage with WHO standard or measured ranges from sand dam water [19][20][21]. Percentage values show the compliance of analyzed water quality parameters with WHO standard, SC = scoop hole, W = well.

Parameter	Scheme	[20]	[19]	[21]
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%**	**-**

2.2. Evaporation and Seepage Losses

In Kenya, some sand dams are found to lose up to 80% of the stored water [11][18]. Evaporation and seepage are the leading causes of water loss [11][32]. The effective storage capacity of a sand dam is a combination of collected sand volume, evaporation, and seepage [11].

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 [27][49]. Evaporation effectively ceases for water stored 60–90 cm below the surface of a sand bed [27][49][50]; however, it depends on the particle size [51][27][49][52]. This is important in ASARs where evaporation significantly exceeds other hydrological components [53]. 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 [11]. 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 [2]. Seepage may lead to low yield and supply capacity [11][32]. About 5% of the total water yield can be lost by seepage [24][33]. To store water for a longer time using a sand dam, the riverbed needs to be fairly impermeable [32]. 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 [32][47].

2.3. 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 [2][15][25][32]. However, Aerts et al. [25] 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 [15]. Therefore, future studies need to consider a network of dams and climate change to assess the possible downstream effect of a sand dam.

2.4. 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 [17]. There is also a lack of cost-efficiency reports of the constructed sand dams [11][2]. Recent studies, for example [12], 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. [11] 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 [2], 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 [6][15].

Siltation affects 40–60% of sand dams [33], and the spillway height and one-stage construction are mentioned as one of the causes of siltation [11], 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 [11]. Despite its reliability in terms of availability, quantity is insufficient for inhabitants and fails to support macroinvertebrates [18].

3. Summary

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. 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 dynamically, 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 experiments 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.

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