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ORIGINAL ARTICLE

Assessing sand dams for contributions to local water security and drought resilience in the semi-arid eastern Shashe catchment, Zimbabwe

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Abstract

Climate change is increasing the frequency and severity of droughts in semi-arid regions. Small-scale water storage can help build drought resilience, particularly in rural areas with no access to formal water infrastructure. Sand dams, which store water by capturing water in sand-filled ephemeral rivers during the wet season, are one promising storage option. While emerging studies indicate tentative evidence of their benefits, the focus on resilience is under-addressed. This study evaluates the impact of sand dams on resilience to climate variability and changes through a participatory case study approach in the Shashe catchment, a semi-arid catchment shared by Botswana and Zimbabwe. Participatory research was conducted via site inspections, focus group discussions, and interviews at 20 sand dams utilized by 19 villages across the Zimbabwean portion of the Shashe catchment. The results show that sand dams significantly improved local water availability, most notably with a significant increase in the number of months per year that water could be collected from the dam site (*mean* = *6.5 months before, to mean* = *10.9 months after construction,* $p < 0.05$). This increase is also reflected in drought years (*mean* = *5.8 months before, to mean* = *9.6 months after construction,* $p < 0.05$). Sand dams also contribute to the adaptive capacity of communities via key benefits such as diversification of livelihood activities, improved health and hygiene, and reduced erosion in the surrounding area due to increased vegetation. In sum, the study demonstrates clear benefits to communities facing drought, supporting calls to elevate sand dams on the development agenda.

Keywords Resilience · Drought · Storage · Sand dam · Water security

Introduction

The impacts of water insecurity and climate change are affecting people around the world. More than two billion people currently live in water-stressed countries (UN Water 2021) and about four billion people experience water scarcity at least 1 month per year (Mekonnen and Hoekstra 2021). Approximately 1.4 billion people live in areas of water vulnerability and stress coupled with variability in water availability and groundwater decline (UNICEF 2021). Global climate change exacerbates these challenges through warming temperatures that cause more frequent and severe

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precipitation events and shift the overall climatic regime (Milly et al. 2008; IPCC 2021). Since 2000, the number and duration of droughts increased by 29% (WMO 2021).

Arid and semi-arid drylands are particularly vulnerable to these challenges. Drylands cover approximately 40% of the global land area and support 45% of the global agriculture (Gaur and Squires 2018; Singh and Chudasama 2021). Extreme intra and interannual climatic variability in these regions presents challenges for economic development and food security (IPCC 2021; Singh and Chudasama 2021). Drylands are especially vulnerable to the rising mean annual temperatures, decreasing annual precipitation, erratic rainfall, and more frequent and severe droughts associated with climate change due to unique characteristics associated with low resource availability, land degradation, biodiversity loss, erosion, and desertification (Gaur and Squires 2018). Rural areas with persistent poverty and low access to social services and infrastructure are at particular risk, such as those found in remote regions of sub-Saharan Africa (Connolly-Boutin and Smit 2016; Serdeczny et al. 2017).

These challenges are prompting calls for resilience, defined here as the capacity to persist and continue to develop in the face of environmental change (Folke 2016). In this context, drylands and the communities who manage and rely on them are complex social-ecological systems that evolve with and adapt to environmental change (Walker 2020; Baird and Plummer 2021). Thus, resilience does not simply measure resistance to disturbance (e.g., engineering, or ecological resilience), but rather describes a dynamic capacity that emerges from both interactions between social (e.g., health, livelihoods, governance) and ecological factors (e.g., biodiversity, reduced erosion). Adaptive capacity contributes to resilience, defined as the ability to learn, innovate, and respond to environmental change (Folke 2016), and is intimately tied to vulnerability (Smit and Wandel 2006) This capacity is broad and subject to many definitions and applications (Engle 2011; Engle et al. 2011) but in most cases focuses on human dimensions associated with social and economic development.

Water storage is a crucial aspect of water security and climate resilience (Grey and Sadoff 2007; World Bank 2023). Water storage contributes to resilience by buffering availability over space and time, enabling a consistent level of water supply. Importantly, storage also contributes broadly to the adaptive capacity of individuals and communities, for example by ensuring household water access for basic health and hygiene, enabling food production through dry seasons or drought years, and supplying continuous hydroelectricity generation (McCartney and Smakhtin 2010). While water storage has historically been synonymous with gray infrastructure such as dams, ponds, and tanks, there is growing attention directed toward natural infrastructure such as aquifers and soil moisture as well as hybrid options such as managed aquifer recharge (de Vriend et al. 2015; Kalantari et al. 2018).

Sand dams are typically viewed as hybrid green-gray infrastructure, i.e., a combination of nature-based and concrete infrastructure, as they comprise concrete or masonry barriers constructed in ephemeral sand rivers to accumulate and store sand. The sand that accumulates behind the dam wall captures and stores water in the sub-surface pore space during the wet season for abstraction during the dry season. Sand dams are suitable for semi-arid regions in particular, because they can be used across a landscape to service remote communities, utilize natural and locally available materials, are relatively inexpensive, and both rely upon and address extreme interannual seasonal flow.

Despite the potential importance of sand dams, existing literature on sand dams' contribution to resilience contains notable limitations, namely (i) focus is mainly on individual impacts rather than a more integrative analysis, (ii) focus is mainly on factors negatively affecting performance rather than unique benefits, and (iii) the rigor of gray literature documents limits the usability of findings. Aerts et al. (2007) and Neufeld et al. (2021) focused on hydrological and soil moisture impacts, respectively, while Ryan and Elsner (2016) and Eisma and Merwade (2021) examined change in vegetation cover (Normalized Difference Vegetation Index, i.e., NDVI). de Trincheria et al. (2015) and Lopez-Rey (2019) evaluate the factors negatively affecting the performance of sand dams, such as siting and siltation, indicating potential challenges with long-term operations. The small number of integrative studies that have been attempted is isolated to specific contexts and do not center on the topic of resilience. Lasage et al. (2008) applied a set of impact indicators that revealed significant positive effects such as 100,000 inhabitants with improved water access, better crop yields, and a 60% average rise in income without a significant impact on the water balance (i.e., storing only 3% storage of yearly runoff). Nissen-Petersen (2006) and Pauw et al. (2008) determined that sand dams support water access for an additional 2.5 months per year. Unfortunately, these studies come with methodological limitations consistent with that of gray literature (Ritchie et al. 2021; Castelli et al. 2022); likewise, the degree to which such studies identify the specific effects of sand dams on resilience (including adaptive capacity) is unclear.

This paper evaluates the impact of sand dams on resilience to climate variability and change through an assessment of villager perceptions of the effects of sand dams in the Shashe catchment, a semi-arid catchment shared by Botswana and Zimbabwe. Twenty sand dams in the vicinity of 19 villages in the Shashe catchment were systematically evaluated through focus groups, individual interviews, and site inspections. The findings were analyzed and synthesized, offering a detailed indication of their benefits, risks, and contributions to resilience.

Methods

Study area and site selection

The Shashe catchment contributes 12% of the mean annual runoff of the larger Limpopo Basin and is shared by Botswana and Zimbabwe. This portion of the catchment extends approximately 19,000 km^2 and incorporates the Districts of Mangwe, Matobo, and Gwanda in Zimbabwe.

Communities have long adapted to the ephemeral flows in the rivers of the Shashe catchment. These rivers flow no more than a few days during the rainy season, becoming surface-dry sand rivers for nine months (or more) during the dry season (Mansell and Hussey 2005). These sand rivers contain surface material eroded from the geology of the surrounding land surface and deposited in river channels, ranging in depths from a few centimeters to more than 20 m in major rivers. Because subsurface flow in these sand rivers is extremely slow, places where sediment is deposited in sufficient depth can become a perennial source of water (de Hamer et al. 2008; Mpala et al. 2020). This water can be abstracted either from open scoop wells or by pumps connected to well points or placed in well screens. People have long been drawing water from the saturated sediment of sand rivers in the Shashe catchment. Where the sediment depth has allowed, commercial farms and the government have used irrigation schemes to abstract water from sand in the Shashe catchment since the late 1950s (Rukuni 1995). Concurrently, small check dams were built on tributary rivers to reduce the siltation in the main dams, which become sand dams. A small number of purposefully designed sand dams were first constructed in the 1980s in the catchment.

Dabane Trust constructed the 20 dams considered in this paper. Dabane initially constructed masonry sand dams but subsequently progressed to sand dam barriers formed from 50% rock and 50% concrete, cast within shuttering. After construction, the sand dam is allowed to mature: a sand bed initially forms upstream and is transported into the dam basin during a heavy storm, which repeats until eventually, the basin fills with coarse sediment that can extend 500 m or more upstream (Fig. 1). Consistent with approaches outlined in Maddrell (2018), the wingwalls are constructed to full design height and the spillway in stages as the volume of harvested sediment reaches the dam wall following storm events. Because fine sediment in a sand dam can obstruct water abstraction, this staged design ensures that only coarse sediment is captured behind the dam wall and cyclonic rains during the wet season are able to pass, transporting fine sediment through the dam basin. The dam is then considered mature and retains clean, abstractable water. Dabane Trust also installs handpumps with livestock water troughs no more than 6 m above the well point and no more than 50 m from the dam basin deep to abstract water from the dam site.

Dabane Trust adapts their design according to the characteristics of a river system. They use surveys and local knowledge to determine the appropriate site and sand dam design and engage local communities in the process of digging the foundation, constructing the wall, and building the spillway and wingwalls. Dabane Trust also implements environmental works and training workshops alongside sand dam construction in efforts to maintain the longevity of the dam and reduce erosion within the dam catchment. Environmental works can include a combination of gabions, stone bunds, live material, silt traps, and/or vegetation planting, which

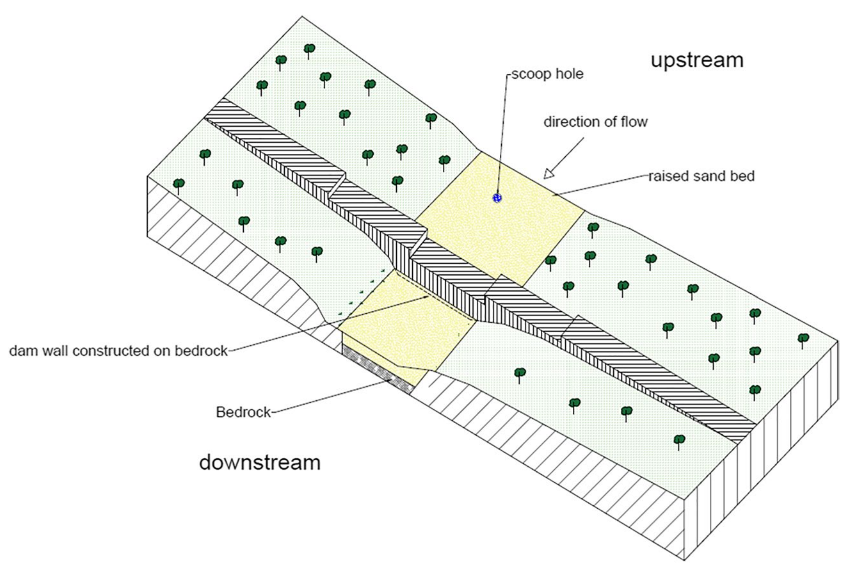

Fig. 1 Typical sand dam cross-section. Upstream of the dam, the sand has accumulated to raise the sand bed and store water. The dam is constructed on bedrock. Downstream of the dam, the sand bed is lower

are implemented to minimize sheet erosion in some cases and = address rill and gully erosion in others.

Specific sand dam sites of focus in this paper were selected according to three main criteria. First, sites with basic baseline data were favored over those with little or none to offer grounds for comparison. Second, sites with earlier dates of construction were favored over more recently constructed dams, as older dams have had more time to mature and to manifest their benefits and risks. Third, sites were selected to ensure a distribution along the (Zimbabwean portion of the) Shashe catchment. In total, 20 sand dams were selected. Two of the dams were situated in one community, so 19 villages were visited in total.

The characteristics of the 19 villages (and 20 sand dams) visited in this study are summarized in Online Resource 1, and their locations in the catchment are depicted in Fig. 2. Asinatheni village has two sand dam sites, in Online Resource 1 as "Asinatheni 1 and 2." These included 19 sand dams constructed between the years of 2003 to 2021, including 14 mature sites, four immature sites, and one dam that failed to mature.

Research framework

Conceptual framework

The conceptual framework was first developed by combining resilience assessment with function evaluation for integrated social and environmental impact assessment (Fig. 3; Slootweg et al. 2001; Resilience Alliance 2010). Resilience assessment guides a systemic investigation of resilience through the identification of a focal system, main issues, and questions of resilience "of what" and "to what" (Resilience Alliance 2010). Function evaluation integrates both biophysical and social benefits and risks within a single framework by focusing on functions for human society as a proxy for measuring environmental changes in situ, similar to the "ecosystem services" or "nature's contributions to people" approach (Millennium Ecosystem Assessment 2013; Díaz et al. 2018).

The framework focuses on the resilience of communities to increasing frequency and severity of droughts via a suite of key benefits and risks. It characterizes the focal system as the sand dam site and the surrounding community that relies on the site for water access. The main issue in the system is the increasing frequency and severity of extreme climatic events, with particular concern for water access during droughts—broadly defined as a "temporary, recurring meteorological event, which originates from the lack of precipitation and is a typical feature of any climate" though a universal definition of drought is elusive (Smakhtin and Schipper 2008). Sand dams are expected to aid in building resilience to these conditions, both by helping maintain key environmental functions (i.e., water availability) and by nurturing adaptive capacity (e.g., promoting livelihoods, health, and hygiene). Thus, the framework focuses on identifying changes in environmental functions due to the presence of the sand dam, with a particular interest in changes during disturbances like drought (i.e., to evaluate changes in resilience), and societal changes derived from these impacts (i.e., to evaluate changes in adaptive capacity). Consideration was also made for environmental changes at higher scales (i.e., upstream and downstream) and processes of reflection and learning that influence the long-term effectiveness of the sand dam.

Analytical framework

Building on the conceptual framework, the analytical framework (Table 1) drew on related past work (e.g., Lasage et al. 2008; Pauw et al. 2008; de Trincheria et al. 2015) to ensure a balance between academic rigor and suitability in a context of rural communities. Each impact was measured via a suite of indicators and through focus groups and/or interviews (see Table 1). The choice of the focus group or interview was determined based on whether researchers and collaborators thought participants' responses would be aided or impeded by answering in a group setting.

Environmental functions investigated include the change in direct water availability, water quality, and erosion due to the presence of the sand dam. The *change in direct water availability* was measured by four indicators. First, the contribution of the sand dam to buffering intra-annual water availability was measured as the change in the number of months per year water could be collected from the site before, versus after dam construction, similar to Pauw et al. (2008) and Nissen-Petersen (2006). Second, the dam's contribution to the relative change in the volume of water available at the household level was measured as the change in the volume of water collected (liters per day) before and after dam construction. This offered a more granular measure than broader indicators like "improved water access" adopted in other studies (Lasage et al. 2008). Third, the contribution of the sand dam to the desirability of the local area (i.e., due to the presence of reliable water access)—and conversely, the risk of adverse consequences of the higher population on adaptive capacity (e.g., land degradation and erosion) as people migrate to the area—was measured as the change in the number of households collecting water from the sand dam site before and after dam construction. Fourth, the contribution of the sand dam to the elevated water table in the area immediately surrounding (100 m) the dam site was measured through questions about the change in the presence of flora surrounding a sand dam before and after dam construction. This approach complements other studies that use remote sensing to indicate changes in NDVI or

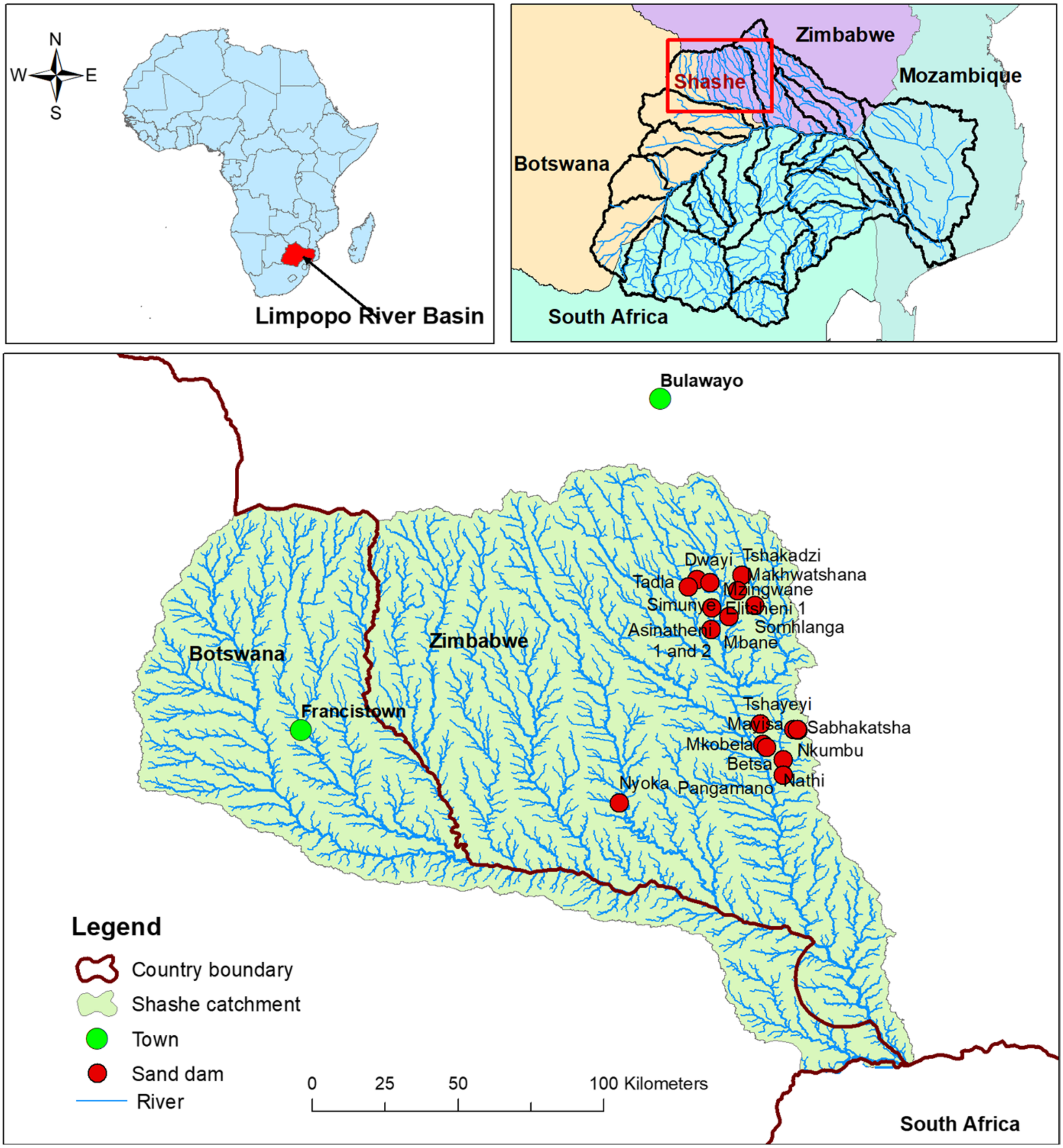

Fig. 2 Map of selected sand dam sites

in situ moisture content via sediment cores (Ryan and Elsner 2016; Neufeld et al. 2021; Eisma and Merwade 2021).

The *change in water quality* due to the presence of the sand dam was measured using two indicators. These include the change in clarity (turbidity, color) and change in the prevalence of water-borne diseases before and after dam construction. This approach complements other studies that measure water quality directly (Ritchie et al. 2021). Finally, the *change in erosion* was measured using three indicators. First, the contribution of the sand dam to reducing erosion was measured as the presence of environmental works at the dam sites and the number of sites experiencing less erosion. Finally, the risk of increased

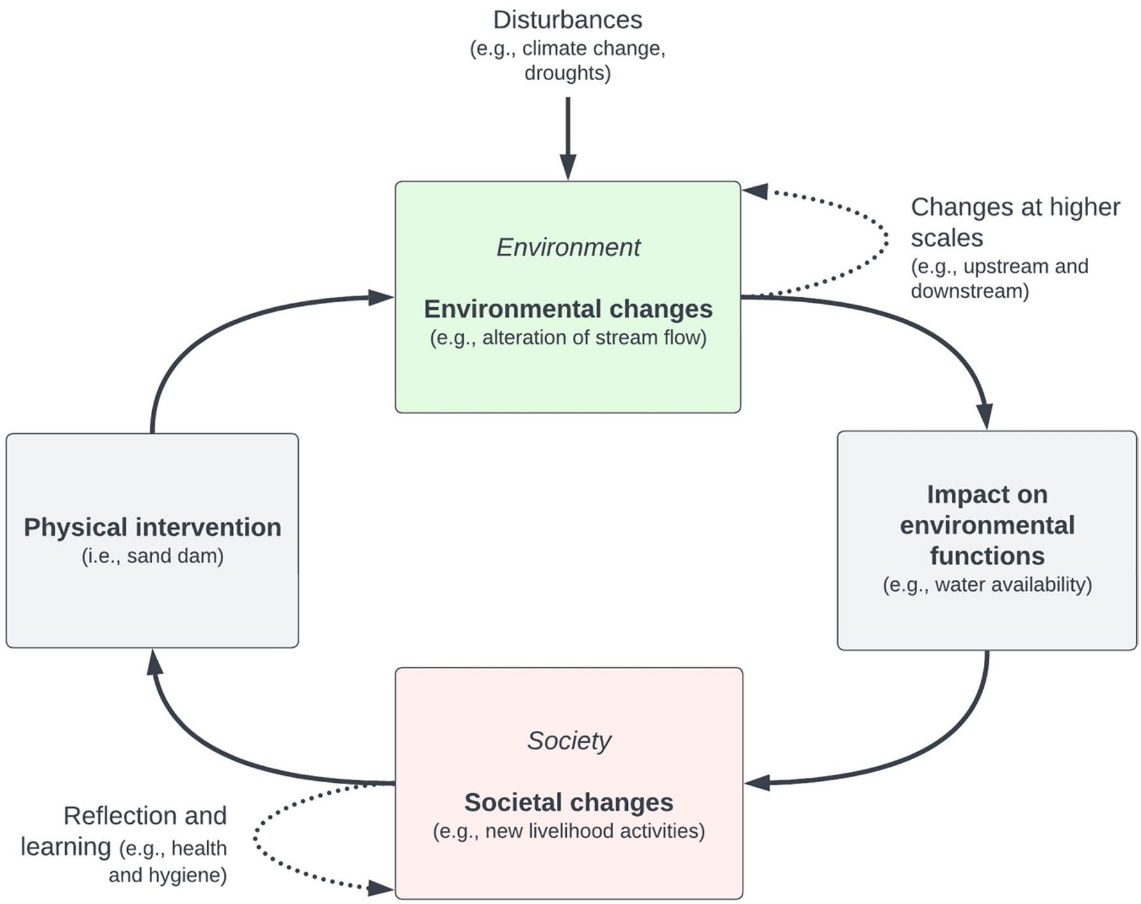

Fig. 3 Conceptual framework combining resilience assessment with function evaluation

erosion due to land degradation was measured as the presence of activities upstream that promote erosion.

The contribution of the sand dam to resilience to disturbances, namely *drought*, was measured using two indicators. First, the contribution of sand dams to buffering intra-annual water availability in a drought year was measured as the change in the number of months water could be collected from the site during a drought year before and after the construction of the dam. This approach complements other studies focused on sand dams and droughts, which adopted alternative methods such as measuring vegetation biomass during drought years before and after dam construction (Ryan and Elsner 2016). Second, the contribution of the sand dam to buffering the social and economic impacts of drought was measured by analyzing which adaptation measures were adopted by community members to mitigate the impacts of drought before and after dam construction. It was assumed that fewer adaptation measures required of community members (e.g., reducing household water consumption) indicate that more water was available at the dam site.

Rather than measuring direct changes to household income like Lasage et al. (2008), four indicators for societal changes due to the presence of the dam were measured. First, the *contribution of the sand dam to freeing time* for other (social, economic) activities was measured as time spent collecting water before and after the dam construction. Second, the contribution of the sand dam to *broader social and economic benefits* via this time resource was measured as the activities pursued with time savings. The contribution of the sand dam to *broader social and economic benefits* via *water availability* (e.g., promoting livelihoods) was measured as the change in the number of sand dam sites with specified water issues before and after dam construction. Finally, the contribution of the sand dam to broader social dynamics was measured as general changes to family dynamics due to the presence of the dam. These societal changes were accompanied by one indicator measuring *reflection and learning*.

Data collection and analysis

Data were collected during site visits at each of the 19 sand dam sites. Participants in the site visits were community leaders and/or individuals involved in relevant local committees (i.e., water point committee, environmental committee,

Table 1 Analytical framework

	Impact	Indicators	Method
Environmental functions	Change in direct water availability due to construction of the sand dam[1]	Change in the number of months per year water could be collected from the site before versus after construction of the dam	Individual interviews
		Change in volume of water (liters per day) collected from the sand dam site before versus after construction of the dam	Individual interviews
		Change in the number of households collecting water from the sand dam site before and after construction of the dam	Individual interviews
		Change in presence of flora surrounding sand dam before and after construction of the dam	Focus group
	Water quality	Change in clarity (turbidity, color) before versus after construction of the dam	Individual interviews
		Change in prevalence of water-borne diseases before versus after construction of the dam	Individual interviews
	Erosion	Presence of environmental works to reduce erosion	Focus group
		Number of sites experiencing less erosion attributed to the presence of environmental works associated with the dam	Focus group
		Presence of upstream activities that promote erosion	Focus group
Disturbances	Drought[2]	Change in the number of months water could be collected from the site *during a drought year* before and after the construction of the dam	Individual interviews
		Adaptation measures adopted to mitigate impacts of drought before versus after construction of the dam	Individual interviews
Societal changes		Time spent collecting water before versus after the construction of the dam	Individual interviews
		Activities pursued with time savings	Individual interviews
		Change in the number of sand dam sites with specified water uses before versus after the construction of the dam	Focus group
		Changes to family dynamics due to the presence of the sand dam	Individual interviews
Reflection and learning		Interviewee learning via involvement with the construction of the dam	Individual interviews

[1]An attempt was made to evaluate impacts on water availability and sediment for communities downstream. However, "downstream" impacts were interpreted as immediately downstream of the dam (i.e., just meters away) as communities benefitting from dams were often unclear on potential impacts further downstream

[2]While attempts were made to capture the extent of flood damage before and after the construction of the sand dam, responses were inconclusive and thus this parameter was not included

dam committee, etc.). Data collection involved a focus group, site inspection, and individual interviews at each site. Eight staff of Dabane Trust who were trained in research ethics protocols conducted the site visits. Four individuals comprised the technical team who managed the site inspection, and four individuals comprised the social team who administered community discussions. Data was collected through a combination of paper and/or digital surveys filled out by the data collection team and audio recordings.

The site visits each began with a focus group that lasted approximately 50 min and involved between 5 and 24 participants with efforts to ensure gender balance (Online Resource 1). The wide range of the number of participants in each focus group was due to differing community sizes and participant availability. The focus group questions were wide-ranging and covered various aspects of the assessment framework. The focus group was followed by a site inspection of the physical state of the dam. Finally, approximately five individuals were asked for follow-up interviews (Online Resource 1).

Data analysis began with synthesizing data across collection techniques (i.e., paper survey; EpiCollect, a secure digital data collection platform; and audio recordings) and normalizing data (i.e., translating to equivalent units). Focus group data had one sample per site ($n = 19$) while individual interviews had 96 samples in total ($n = 96$). Statistical analyses on these datasets were conducted in Excel. For variables with appropriate data before and after dam construction, a *t*-test (paired two-sample for means) was conducted to identify whether the sand dam caused a significant change in the variable (e.g., number of months per year water could be collected from the sand dam site before and after construction of the dam). Simpler descriptive statistics (e.g., averages, percent change, etc.) were determined for data that were less compatible with more rigorous statistical calculations.

Results

Impact on environmental functions and users

The sand dams improved direct water availability in ways that may directly improve the community's capacity to adapt to drought events and other disturbances. There was a significant increase in the number of months water could be collected from the sand dam site after construction (*mean (m) = 10.9 months, variance (v) = 4.5*), compared to before (*m = 6.5 months, v = 6.1), t(96) = -17.6, p < 0.05*. This improvement in water availability was affirmed by an average of 58 l per day increase in the volume of water collected for household water use by interviewees after the construction of the sand dam (*standard deviation = 105; maximum increase = 340 L/day, minimum = -166 L/day*), as depicted in Fig. 4. A minority of interviewees indicated a decrease in the volume of water collected, which may be due to socio-economic factors that reduce household consumption (e.g., as family members migrate elsewhere), though further investigation would be required to identify the cause.

There was no significant change in the average number of households collecting water from the site in both the wet and dry seasons after dam construction *(dry season: M = 45, V = 1488)* compared to before *(dry season: M = 38, V = 1164), t(85), p > 0.05*. This lack of significant change may be because families involved in sand dam construction may remain the primary users as the local population fluctuates. However, this data varied widely (Fig. 5a): the wet season saw from − 240 (fewer) to + 40 (more) households, while the dry season saw from − 80 (fewer) to + 240 (more) households. Thus, while the *t*-test revealed no significant change, 57% of interviewees noted a net increase in the number of households collecting water from the site in the dry season (24% net decrease, 26% no change), and 49% noted a net increase during the wet season (29% net decrease, 14% no change).

The presence of indigenous grasses and trees can improve resilience, for example by improving soil moisture storage and reducing erosion during high flow events. The sand dam increased the presence of indigenous grasses and trees at most sites (Fig. 5b). This phenomenon indicates a higher water table in the surrounding area due to the presence of the sand dam. Moreover, this vegetation can help reduce erosion from river banks as it holds the soil in place, helping maintain the integrity of the sand dam.

The presence of the sand dam improved water quality. When asked about changes in clarity (turbidity, color), 65% (62 of 96) indicated an improvement, 26% (25 of 96) indicated no significant change, 8% indicated a decline (8 of 96), and for 1% (1 of 96), the data was unclear. There was a perception among interviewees who indicated a decline in water quality that the water had a reddish color due to the rusting of the pump. However, the handpump does not have metal parts that come in contact with the water for an extended period of time. Thus, the reddish color may be due to the

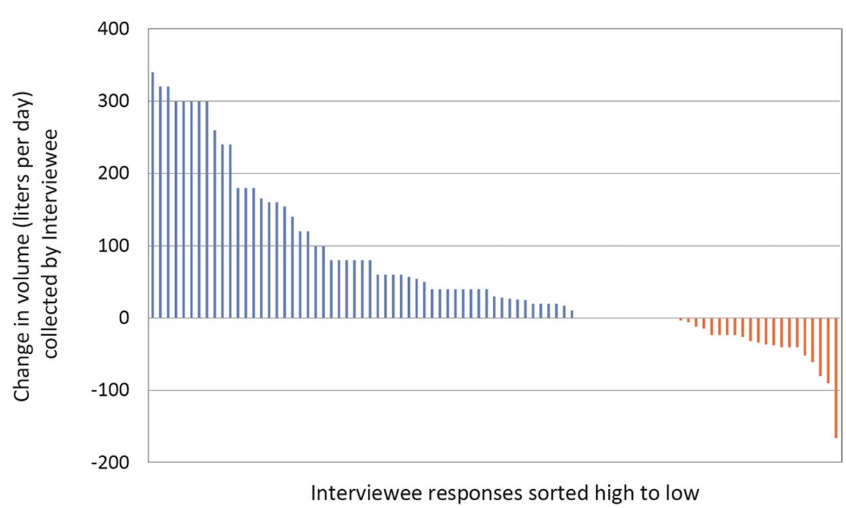

Fig. 4 Change in volume of water (liters per day) collected for household water use by participants after construction of the dam ($n = 96$ interviewees)

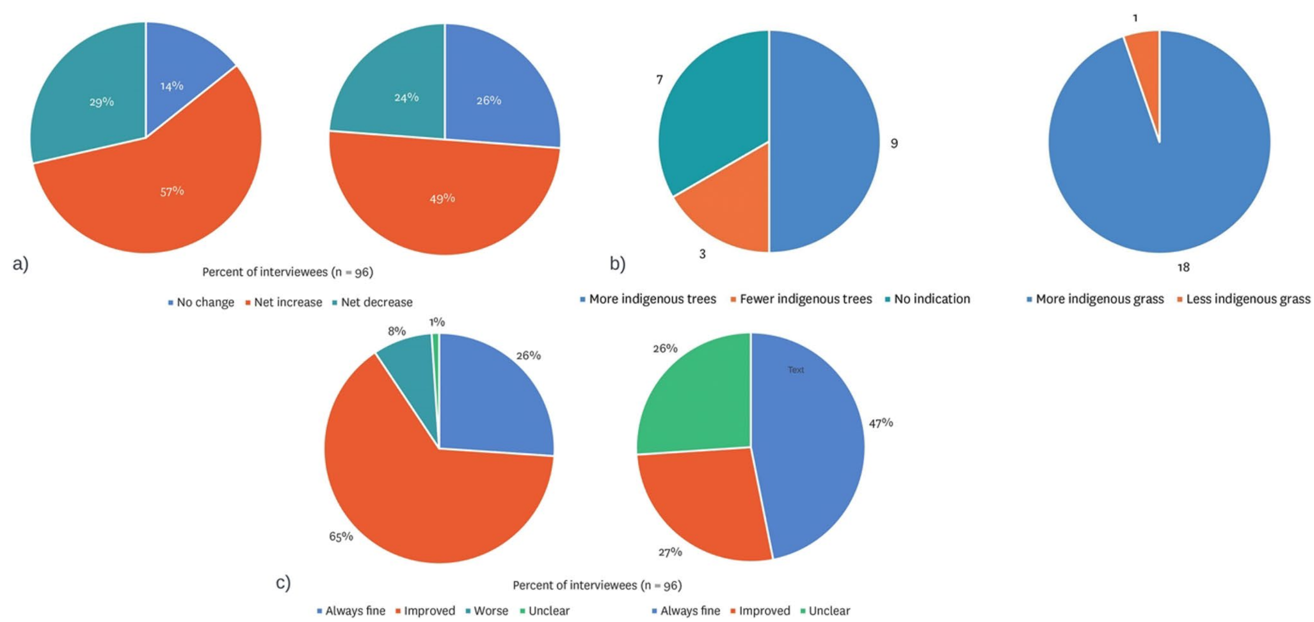

Fig. 5 Reported impact of the sand dam on key indicators from the analytical framework. **a** Percent of interviewees ($n=96$) reporting a net increase, decrease, or no change in the number of households using the sand dam site. Results for the dry season are on the left. Results for the wet season are on the right. **b** The number of sites ($n=19$) with the stated changes in flora due to the presence of the sand dam, indicating a higher groundwater table. Changes in the presence of indigenous trees are on the left, and changes in the presence of indigenous grass are on the right. **c** Number of interviewees ($n=96$) reporting changes in water quality due to the presence of the sand dam. The change in clarity (turbidity, color) is on the left, and the change in prevalence of illnesses is on the right

high incidence of iron salts in groundwater in some areas of the district, which would accumulate in the sand dam basin.

When asked about changes in the prevalence of water-borne illnesses, which contributes to adaptive capacity through improved health, 47% (45 of 96) indicated there were no issues with water-borne illnesses to begin with. However, of the remainder, 27% (26 of 96) indicated improvements in upset stomach, diarrhea, cholera, bilharzia, and/or malaria, and for 27% (25 of 96) the data was inconclusive (Fig. 5c). These stated water quality improvements should be confirmed with water quality monitoring.

How the sites are maintained long-term may indicate the degree to which sand dams are embedded into community resilience to drought events over the long term. Of the 19 sites, thirteen of them had an active Environmental Committee that had implemented additional environmental works after dam construction, including gabions (10 sites), stone bunds (8), live material (3), silt traps (2), vegetation planting (2), and gully reclamation (2). Focus group respondents at all 19 sites claimed there was less erosion due to the presence of the environmental works. However, of the nineteen sites, brick molding (10 sites), scoopwells upstream (9), deforestation (6), sand extraction (4), laundry activities (2), and gold panning (1) were present, potentially influencing the storage capacity and longevity of the sand dam site. Moreover, several sites had physical issues with the most common being trails from livestock along the wing wall (8) and broken aprons (7), in addition to cutting around the wing wall (4) and cracks and seepage through the dam wall (4).

Disturbances

The sand dam improved drought resilience. During a drought year specifically, there was a significant increase in the number of months water could be collected from the sand dam site after construction ($M=9.7$ *months*, $V=11.3$), compared to before construction of the sand dam ($M=5.8$ *months*, $V=8.8$), $t(96)=12$, $p<0.05$. Moreover, communities at fewer dam sites needed to adopt adaptation measures during drought years (Fig. 6), indicating that the sand dam improved drought resilience enough that these adaptations were no longer required.

Societal changes

Societal changes indicate changes in a community's capacity to adapt to changing conditions. There was a significant decrease in the amount of time spent collecting water after dam construction ($M=0.6$ *h*, $V=3.5$), compared to before ($M=1.6$ *h*, $V=7.4$), $t(96)=3.8$, $p<0.05$. With this free time, interviewees were able to pursue activities that improve adaptive capacity, such as income-generating activities (46 of 96 interviewees), doing household chores (40), gardening (23), and spending time with family, community, or resting (12).

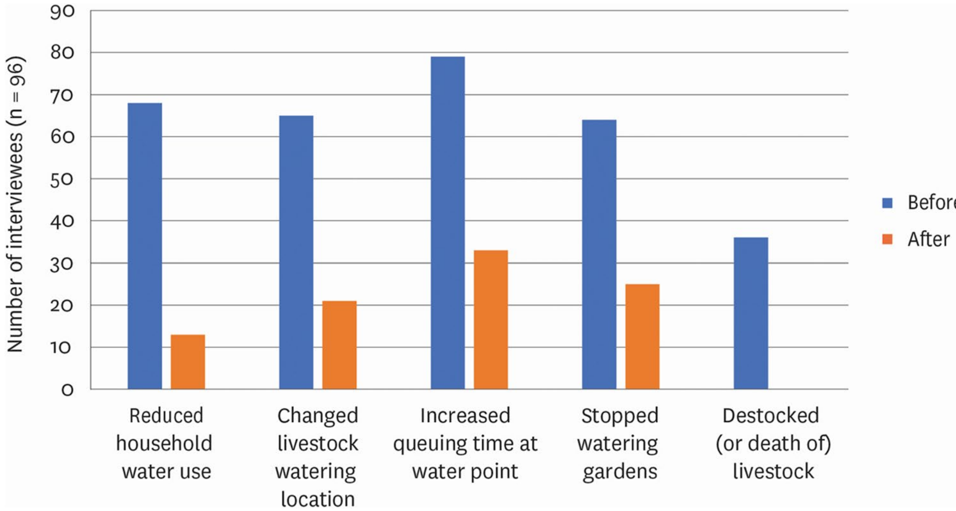

Fig. 6 Change in adaptation measures reported by communities before and after sand dam construction ($n = 96$ interviewees)

Notably, many interviewees also cited the benefit of improved community peace and family cohesion after dam construction (52 of 96), in addition to improved health and hygiene (19).

The diversity of water use changed after dam construction, which further improves resilience to changing conditions. While all sites continued their use of the dam for household water, more sites began using water for kitchen gardens (from 9 to 13 sites), livestock (from 11 to 16 sites), and other livelihood activities (from 8 to 10 sites). Improved livestock health was also indicated at eight sites due to improved water availability, as respondents stated that cattle were driven from two to 20 km to the nearest water point for at least part of the year prior to sand dam construction. Water use for brushwood gardens and brick molding declined**,** which may be attributed to increased knowledge regarding their detrimental impacts on erosion and dam effectiveness.

Reflection and learning

Construction of the sand dam and associated activities (i.e., environmental works, trainings) offered opportunities for learning at some sand dam sites. When asked about what interviewees learned through their experience with the sand dam, 45 of 96 interviewees mentioned the importance of environmental works (45 of 96), sand dam and pump design and maintenance (16), health and hygiene (15), income generating activities (7), and the importance of water conservation (3).

Discussion

The potential of sand dams has long been speculated. Nevertheless, previous studies provided only tentative and piecemeal evidence of the resilience and adaptive capacity benefits of sand dams, and as such, the reliability and comprehensiveness of these evaluations have been flagged. This study is believed to be the first to place resilience at the center of a sand dam assessment through an analysis guided by a framework that combines function analysis and resilience assessment. Moreover, the study complements integrative studies from other contexts (e.g., Lasage et al. 2008) to suggest benefits of sand dams can be realized in a broad swath of geographies. The results of this study can be distilled into four key messages.

First, there was a significant improvement in water availability due to the presence of the dam, indicating that the dam improved the resilience of these villages to adapt to climatic variability. This was most notably measured as an average increase of 4.4 additional months per year that water could be extracted from the riverbed at the dam site and further supported by an average increase of 58 l of water collected for household water use per day. The average of 4.4 additional months of water availability per year exceeds the additional 2.5 months per year determined by Pauw et al. (2008) and potentially supports the large number of inhabitants with improved water access in the Kenya case by Lasage et al. (2008). The difference between the findings of this study and that of Lasage et al. (2008) may be due to a range of context-specific factors, in particular the differences in the local climate.

Second, sand dams contribute to community resilience to the increasing frequency and severity of droughts. The clearest indicator is the improvement in water availability during the dry season, most notably as an increase of 3.9 months of water availability per year during drought years. This improvement reduced pressure on communities to adopt restrictive adaptation measures. This finding is consistent with identified improvements in adaptive capacity during droughts via vegetation biomass (Ryan and Elsner 2016).

Third, sand dams contribute to the adaptive capacity of communities to both climatic and socio-economic disturbances by enabling diversification of livelihood activities (i.e., through improved water availability and time savings), improving health and hygiene (i.e., via improved water quality), and supporting community peace and cohesion. These findings are consistent with those of Lasage et al. (2008) in Kenya, which identified a rise in income due to the presence of the sand dam (i.e., the 60% average increase) as well as greater crop variation and industrial capacity. Our findings nonetheless identified the presence of local activities (e.g., brickmoulding, deforestation, gold panning) which may adversely affect dam performance through siltation, as indicated in reviews by de Trincheriea et al. (2015) and Lopez Rey (2020). These findings indicate a potential role for sand dams in improving adaptive capacity. However, because adaptive capacity implicates broad and complex social and economic changes, the generalizability of these findings to other geographies and contexts requires further investigation.

Fourth, sand dams contribute to environmental enhancement in ways that further improve resilience to both floods and droughts. More indigenous grasses and trees were present in the area surrounding the dam at the sand dam site after construction, indicating an increased water table. Importantly, these findings indicate how the concrete dam not only improved resilience due to the availability of water. It also improved the resilience of the surrounding social-ecological landscape, as more vegetation reduces the potential for erosion during flood events and improves dam effectiveness by slowing the flow of water. This was evident at all 19 sites. The observed presence of more indigenous grasses and trees surrounding the dam site supports the increased presence of vegetation detected in prior studies using remote sensing (Ryan and Elsner 2016; Eisma and Merwade 2021).

Several limitations of the study should be acknowledged. First, the focus group size varied. In two communities (Pangamano, Tshakadzi), relatively low participation was due to community politics. In other cases, the focus group size reached 24 which may have posed challenges in ensuring all voices were heard. Moreover, certain questions were difficult for community participants to respond to and thus generated inconclusive results, such as questions regarding the impact of the sand dam on flood risk or on communities downstream. Second and perhaps more significantly, the long recall period required for villager responses may have at times compromised their accuracy. Third, the format of the questions required for community participation did not allow for the nuance needed to track the performance of sand dams over time. Thus, while only one sand dam had failed to provide a perennial source of water, the long-term sustainability of the sand dams remains a question. Last, it must be acknowledged that most selected sites were in the eastern portion of the catchment, and a more balanced distribution of sites may have generated a slightly different assessment of sand dam impacts.

Conclusion

The paper supports the role of sand dams in improving water security and drought resilience in semi-arid climates. The most notable finding is the significant increase in the number of months water could be extracted from the site over the course of a year, including during a drought year, which relieves pressure on communities to adopt restrictive adaptation measures. Broader social and ecological benefits of sand dams provide additional contributions to adaptive capacity. As other, more conventional storage infrastructure such as large dams or deep aquifers may either not support rural communities or be subject to complex hydrogeological dynamics, sand dams are believed to present a somewhat unique and accessible option.

This study points to at least four persistent research gaps. First, long-term water quality testing is required to determine whether the sand dam plays a significant role in either filtering out or accumulating minerals and potential contaminants. Second, longer-term studies are required to determine the buildup of water storage potential as the sand dam initially matures and conversely the long-term deterioration of sand dam storage as a sand dam ages. Such research includes not only identifying the factors influencing the long-term performance of the sand dam, but how they can be mitigated. Third, suitability maps and pilot studies are required in regions beyond East and Southern Africa to determine where, and under what conditions, sand dams may be a uniquely suitable innovation to improve drought resilience in semi-arid regions. Fourth, in situ triangulation of perception-based findings presented in this paper would serve to corroborate and reinforce key results. For example, field plots could be developed around sand dams to determine the degree to which erosion changes following sand dam construction.

Regardless, the findings point to the significant potential for sand dams to provide community benefits and contribute to resilience in other semi-arid regions. Coupled with findings from other investigations (e.g., Lasage et al. 2008), there is a mounting weight of evidence that sand dams do indeed deliver the benefits they promise across the regions they have been constructed. While there is undoubtedly a need to continuously adapt and strengthen the roll-out of sand dams, rural development practitioners and policy-makers in semi-arid regions can adopt the findings of this study in five ways:

- *Put sand dams on the map as a response to climate change in semi-arid landscapes*. Watershed management agencies and other policy-makers in semi-arid regions can integrate the investigation of sand dam storage potential as part of a more comprehensive water storage plan. Doing so will help fill gaps in rural water storage, particularly in regions with few or no alternative water sources.
- *Ensure that sand dams are employed toward their unique role in cultivating resilience—for which there may be no alternative*. Sand dams' role and comparative advantage are adaptation and resilience for rural communities. While the direct economic benefits of sand dams may be outweighed by the benefits of other storage infrastructure, other infrastructure is unlikely to offer resilience and adaptation benefits to rural communities. Sand dams may simply play a role that other infrastructure cannot.
- *Adopt an iterative, learning, and strengthening approach in partnership with communities.* Sand dams are best implemented in true partnership with local communities who benefit from and are responsible for maintaining the dam. Agencies funding and implementing sand dams should recognize that sand dam design and implementation may need to be adapted to new contexts and thus require an iterative, learning approach.
- *Recognize second-order benefits of sand dams that improve broader adaptive capacity.* Appreciate that there are resilience benefits, e.g., in terms of broader environmental change and income diversification, which may not be captured in conventional planning efforts
- *Explore opportunities to scale solutions to improve landscape resilience*. There may be potential to harness the multiplier effects of sand dams, e.g., on broader landscape changes, through a more widespread rollout.

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Data Availability The authors confirm that relevant data to support the findings of this study are available within the article and its supplementary materials. The raw data from research participants are not publicly available, as they may contain information that could compromise the privacy of research participants.

Declarations

Ethics approval and consent to participate The study was reviewed and received ethics clearance through the International Water Management Institute International Review Board, which included provisions for informed participant consent.

Conflict of interest The authors declare no competing interests.

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