Journal of Arid Environments 188 (2021) 104472

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Assessment of water presence and use at sand dams in Kenya

Doug Graber Neufeld[a,*], Joseph Muli[b], Bernard Muendo[c], James Kanyari[d]

[a] Eastern Mennonite University, Department of Biology, Eastern Mennonite University, Harrisonburg, VA, 22802, USA
[b] Utooni Development Organization, PO Box 89, Kola, Machakos, Kenya
[c] Sahelian Solutions Foundation, PO Box 85, 90200, Kitui, Kenya
[d] Mennonite Central Committee Kenya, 67 Mangu Gardens, Westlands, Nairobi, Kenya

ARTICLE INFO

Keywords:
Sand dams
Water harvesting
Rural water supply
Climate adaptation
Water access

ABSTRACT

Levels of water access provided by sand dams were assessed by measuring water presence and use in a representative sample of 97 dams in Kenya. Most dams were filled with sediment capable of holding water, with a 25% median reduction of water capacity due to siltation when using a high estimate for sediment specific yield. Multiple sediment cores taken from each dam indicated the presence of water in over half of sediment cores from 57% of dams. Although there is individual variation, generally dams in the region were therefore capable of accumulating water. Analysis of Landsat satellite images indicated that this did not translate into an average increase in vegetative greening and moisture indices at dam sites compared to controls sites. Observational data on activities at dams indicated variable levels of water use; only 43% of dams had active water harvesting present, and only 39% of dams had current agricultural activities adjacent to the sand dam site. Cross-sectional comparison of data did not indicate consistently higher levels of water harvesting or agricultural use at dams with more water. Results point towards a high level of community understanding of sand dam benefits, but a lower rate of actually realizing those benefits.

1. Introduction

Globally, rural communities living in semi-arid regions are largely rainfed agricultural communities that face perennial shortages of water (see Villani et al., 2018), with a main problem being the uneven and unpredictable distribution of water (Biazi et al., 2012). Sand dams are a type of decentralized water infrastructure that enable communities to utilize water resources more efficiently by collecting water during rainy periods for use during later dry periods. These solutions are becoming increasingly important as expanding arid and semi-arid lands are especially susceptible to climate change (Lasage et al., 2015), and at the same time increasingly seen as destinations for settlement as the human population expands to available lands. While sand dams are expanding in their usage across the African continent, and other parts of the world (Villani et al., 2018), the semi-arid Ukambani region of southeastern Kenya remains the epicenter of sand dams. Sand dams have been built in the region since the early 1900's by governmental and non-governmental organizations, with estimates of several thousand sand dams in the region (Viducich 2015).

Sand dams have substantial appeal in these regions for a variety of reasons which have been outlined by others (e.g. Teel 2019). While the details of engineering design are critical (Quilis et al., 2009), they are conceptually simple and visually easy to understand (Fig. 1). A concrete dam is built on bedrock across an ephemeral stream, and the area behind the dam then fills with sand during the seasonal storms which occur in the region. Significant volumes of water accumulate in the pore space of the sand, which is protected from evaporation and thus provides a source of water into the dry season, recharging the local aquifer (Aerts et al., 2007; Hoogmoed 2007). While upfront costs are significant, life cycle costs are low compared with other means of providing water (Lasage and Verburg 2015). The tradition of self-help groups in the region lends itself to the communal nature of sand dams (Teel 2019), which are planned, implemented and managed as groups rather than as private landowners (Lasage et al., 2008).

The potential benefits of sand dams to communities are diverse and have been well documented in a number of studies. Benefits are both direct, such as decreasing the distance needed to walk for water or increasing agricultural product (Lasage et al., 2008; Teel 2019), and indirect, such as a host of economic, health, and other quality-of-life indicators (Lasage et al., 2008; Pauw et al., 2008). In addition,

* Corresponding author.
E-mail addresses: neufeldd@emu.edu (D.G. Neufeld), josephmutinda362@gmail.com (J. Muli), bernard@sasolfoundation.co.ke (B. Muendo), jameskanyari@mcc.org (J. Kanyari).

https://doi.org/10.1016/j.jaridenv.2021.104472
Received 22 January 2020; Received in revised form 22 October 2020; Accepted 11 February 2021
Available online 22 February 2021
0140-1963/

potential benefits extend to resilience of the local ecological community, as illustrated by the recent quantifications of increased vegetative greening at four select sand dam sites (Ryan and Elsner 2016).

Others have cautioned that while the theoretical benefits are clear, in practice there are some key challenges which have severely limited their effectiveness. Some questions have been raised about the effectiveness of dam structure itself in accumulating sand, with concern centered around the degree to which siltation decreases the ability of dams to hold water (de Trincheria et al., 2015; Viducich 2015; de Trincheria and Otterpohl 2018). In other cases, the questions center on whether effectiveness has been hindered in some instances by the lack of appropriate social structures at a community (Cruikshank and Grover 2012). For the Ukambani region of Kenya, it's not clear whether sand dams in the colonial era had an impact during the period of increased agricultural productivity– the seminal study of land use changes at that time in Ukambani does not mention sand dams as a defining activity that helped change the region (Tiffen et al., 1994). Thus, there is some lack of clarity on the degree to which the potential benefits of sand dams have been realized.

This study was undertaken to get a more representative picture of some key physical and social parameters at sand dams that determine both the water presence and the water use components of water access. In particular, this study minimizes biases in making conclusions about sand dam efficacy by: 1) using a semi-randomized selection of sand dams to get a more representative sample of dams, 2) collecting data from a statistically robust sample size, and 3) relying on both observational data collection from the dam sites, and self-reported survey data from the communities.

2. Methods

2.1. Study design

We assessed water access as one measure of sand dam effectiveness by measuring multiple parameters of water presence and use. This study took a mixed methods approach, collecting a suite of physical and social parameters that were quantifiable either as discrete or rank scored variables, and combining this with qualitative data collected in community survey responses. Analysis was a combination of observational conclusions, and cross-sectional comparisons correlating water presence with water use. The study was designed with a large sample size and semi-random design (see section 2.2) in order to ensure generalizability of the conclusions.

2.2. Sand dam selection and visits

We visited a total of 97 sites to give statistically representative results of the region (within the 10% confidence interval), based on the estimated total number of dams (several thousand). Initial sand dam sites were randomly selected from lists of dams from two local nongovernmental organizations that have constructed a large number of sand dams in the region: Sahelian Solutions Foundation, Kitui (SASOL; list of 505 dams), and Utooni Development Organization, Machakos/Makueni (UDO; list of 448 dams). Because records of sand dams constructed from earlier (early 1990) were not kept, selected sites mostly represented dams that were not older than 20 years. Lists were randomly ordered, and the first 40–50 dams from each of the UDO and SASOL lists were taken as the initial selections. Alterations of selected dams were needed in 12 cases where dams could not be located or records were otherwise inaccurate. In those cases, we selected a substitute dam near the site that could not be found, or sites were dropped and the next on the list was added to the selection. Data was collected from 49 UDO dams, and 40 SASOL dams. In addition, some data representing older dams was collected by including eight colonial-era sand dams (1950's or early) in Kitui that were identified as part of a parallel project. This study therefore has a mostly randomized design drawing from the lists of dams from the two NGOs, with the caveats that: 1) lists of known dams only represent more recent sites, 2) not all dams could be located, and were sometimes replaced by nearby dams, and 3) a small number of selected colonial-era dams was included.

Sand dams are not evenly distributed throughout the region, since some areas have more communities, and since many communities will build additional dams once an initial dam is built. Thus, locations of the sand dams randomly selected for this survey tended to be clustered in certain regions (Fig. 2). All areas had the same distinct dry seasons (Jan–Mar; Aug–Oct) and wet seasons (Apr–July; Nov–Dec). Since sand dams are designed to provide an extended water source during the dry season when other water sources are not available, surveys were conducted in the dry seasons (Aug–Oct 2016 and Jan–Mar 2017). GPS coordinates were collected for each site, both at the centerpoint of the sand dam structure and at the drawback point (the estimated furthest upstream point of sediment accumulation).

2.3. Water content

We estimated the potential storage volume of sand dams by multiplying the estimated volume of sediment by the estimated specific yield (the free space in sediments holding extractable water). We did not have a way to estimate the impact of the adjacent aquifer, and so did not include this in the estimate. The calculated water volume therefore is most likely a lower bounds of the theoretical potential water volume of the sand dam.

2.3.1. Sediment sampling and particle analysis

A soil corer with extender (Forestry Supplies) was used to sample the substrate in sand dams to a maximum of approximately 1.5 m. In most cases, it was not possible to get a sample to this depth, due to the hard nature of the substrate (such as coarse sand making it difficult to use the corer, or compacted dry silted sand); the average core depth was 0.7 m. In cases where substrate was very loose, or very crusted, a shovel was used to dig an initial hole. Substrate removed from the hole was mixed and then filled the corer to the depth of the hole, as an estimated

Fig. 1. Two examples of sand dams in Ukambani. Sand dam in left panel has intact dam face, functional scoop holes for water collection (surrounded by brush to exclude livestock), and evidence of green vegetation. Sand dam in right panel lacks of any evidence (such as water collection site, vegetative greening) of water accumulation, and vegetation growing on sediment surfacing suggests siltation which would limit effective storage of water. Blue arrows indicate direction of water flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

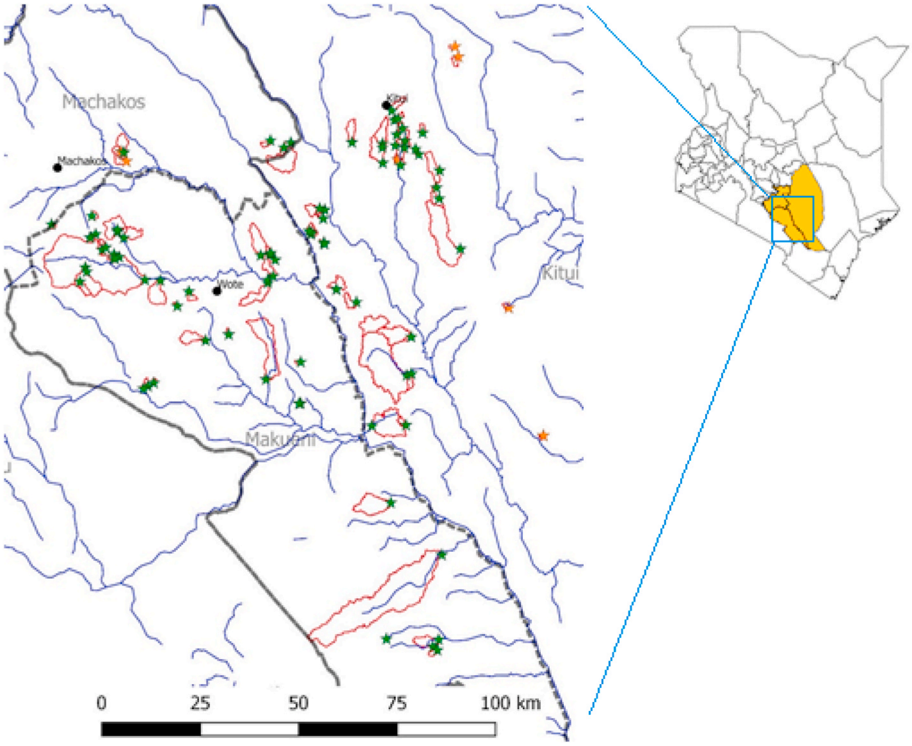

Fig. 2. Location of sand dams that were surveyed, relative to major waterways and county boundaries. Sites in green are UDO and SASOL dams. Sites in orange are colonial-era dams. Watershed areas draining into the sand dams are shown in red outlines. Yellow counties shown on Kenya country map are Machakos, Makueni and Kitui. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

representative sample.

Four cross-sectional sites were selected at the dams for sediment coring. The first site was approximately two meters upstream from the dam structure. The other three sites were roughly ¼, ½ and ¾ of the distance from the dam structure to the drawback. At each cross-sectional site, three cores were taken, at distances ¼, ½ and ¾ across the width of the dam at that site. The three cores at each site were then pooled and stored in a plastic bag while transported to the labs at SASOL or UDO for analysis. Samples were analyzed gravimetrically based on USDA methods (Soil 1996). Samples were thoroughly air-dried, and then ground in a mortar and pestle. Samples were then separated in a set of 3 particle sieves (Forestry Supplies; mesh for 0.063, 0.250, 0.500 mm) by manual shaking for 10 min, in order to separate sediments into broad size classes (0–0.063 mm, 0.063–0.250, 0.25–0.5 mm, and >0.5 mm), which approximate USDA size classes. Collected particles in the separate sieve trays were weighed to the nearest 0.1 g on a portable scale (Ohaus).

The useable water content of sediments varies according to the size of the particles (usually expressed as particle radius in microns), with smaller particles having lower useable water content. The actual amount of useable water in a complex mixture of particles is not exactly defined in the literature. We therefore used two boundary estimates for common particle size classes based on minimum and maximum specific yields reported by Johnson (1967) (Table 1).

Table 1
Estimates of specific yield (amount of "useable" or "extractable" water) in standard particle size classes (Johnson 1967).

particle size (microns)		Estimated useable water as percent of total volume	
		Low estimate	High estimate
Fine Gravel	**2000+**	21%	35%
Coarse Sand	**500–2000**	20%	35%
Medium Sand	**250–500**	15%	32%
Fine Sand	**63–250**	10%	28%
Silt & Clay	**0–63**	0%	19%

Total water volume based on the low and high estimates for useable water was compared to the theoretical total water volume of dams if the dam were entirely filled with coarse sand (*i.e.* an "ideal" dam with respect to particle size). This gives an estimate of the degree of siltation as the percent reduction in useable water due to the presence of the smaller particles.

2.3.2. *Volume of sand dam*

The volume held behind a sand dam was estimated using a simple geometric model (Teel 2019). We used the 2-D polygon outlined by the dam structure itself, taking the spillway level as the top surface, and the measured dam structure depths to define the irregular polygon. The polygon shape was taken as representing the geometry at the measured intervals back to the drawback. At each interval, the width of the polygon was adjusted to the measured width of the dam, and the height of the polygon was adjusted linearly based on the distance from the dam structure to the drawback (for example, the depth of the dam at half the distance from dam structure to drawback is assumed to be half the full depth at the dam structure). The dimensions of the concrete dam structure itself was assessed using a laser distance finder (Bosch GLM 80) and a conventional tape measure. The depth of the dam structure was measured on the downstream side at intervals spaced to get at least 7 depth measurements.

The width of the area accumulating sand behind the dam was measured starting immediately upstream from the dam structure, and then at intervals of 10–50 m (depending on the drawback of the dam; shorter dams had closer measurement intervals). The lateral boundaries were judged as the transition from sand to soil, and/or a bench where the ground was obviously raised. The drawback was normally estimated as a constriction in the channel, often with the presence of rocks, that signaled a transition from flat sand or soil, to a more rocky or uneven channel that appeared to have been unaffected by substrate accumulation. In a minority of cases, the channel itself was evened sand or other substrate, and a definitive drawback was more difficult to identify. Usually these were in dams with a long drawback (more than 400 m, for instance), and we estimated the location of an approximate transition from the dam to the unaltered river bed.

2.3.3. Condition of sand dam structure

The general condition of the sand dam structure was assessed subjectively. Any evidence of damage, leakage (e.g. staining, or pooling of water below dam), or erosion was noted. A standard set of photographs (e.g. dam face, surface across the back of the dam, etc) was taken to document the dam for later verification. When present, erosion was classified as slight (small area of minor erosion), moderate (about one to three quarters of the dam face shows evidence of minor erosion), or severe (most of the dam face shows some erosion, or there are areas of major erosion). Degree of sediment filling was judged at the dam by comparing the level of sediment behind the dam to the height of dam as seen at the face; dams were classified as not at all filled, ¼, ½ or ¾ filled, or fully filled.

2.4. Normalized distribution vegetation index (NDVI) and normalized distribution moisture index (NDMI)

Satellite images were used to measure increased vegetative greening and moisture of sand dams, compared with similar measurements at comparable control stretches of the waterway upstream or downstream (depending on the presence of other adjacent sand dams) from the sand dam, measured from the structure or drawback, respectively. Control stretches were assessed at both 200 m and 400 m distance from the sand dam, based an estimated zone of groundwater influence of 350 m (Quilis et al., 2009). Data were integrated in a 30 m and 100 m buffer range out from the center of the waterway stretching from the dam site to the drawback. We excluded data from sand dams where additional sand dams were identified on the waterway within 400 m of the control points.

Both NDVI and NDMI were assessed as measures of vegetation impacted by the presence of moisture presence (Lin et al., 2009). The NDVI is a standard method of estimating green vegetation health and density (Klisch and Atzberger 2016; Hausner et al., 2018), and was calculated from Landsat 8 images, bands 4 and 5. Calculated values were between 0 and 0.5, with higher values indicating more greening. NDMI is an independent vegetative index which estimates moisture levels (Gao 1996) calculated from bands 5 and 6 of the Landsat 8 images, with higher values indicating more moisture content of vegetation and soil. At each site, two images from different years in the 2014–2017 period were analyzed for each dry season (Feb–Mar, and Sep–Oct, with specific dates depending on dates of available images that were free of cloud cover). Images from path 167–168, rows 59–61 were downloaded from the USGS GloVis site (https://glovis.usgs.gov/), and analyzed with QGIS; spatial resolution of images was 30 m.

2.5. Observational data

At each sand dam, observational data on water presence and use was collected by assessing 1) the presence of water in sand cores, 2) evidence of water harvesting from the dam, and 3) evidence of agricultural activities benefiting from water collected at the sand dam. Water presence in sand cores was documented during the coring process for sediment size (see section 2.3.1) in which four cross-sections of three samples each was collected. We calculated the percentage of cores containing water as an estimate of water presence at the dam at the sampling date. Water harvesting activities were assessed by recording any evidence of harvesting, such as scoop holes (used or unused), open wells, and the presence of water pumps or other equipment. Agricultural uses of the land near dams was quantified by conducting transects; land use was estimated on 30 m transects laterally from the dams, at 15–50 m intervals (depending on the size of the dam). Records of land use were categorized as bushland, unused cropland, presently used cropland (dryland crops such as maize, beans, etc), vegetable fields (those requiring irrigation such as cabbage, etc), cultivated grass (e.g. napier grass), fruit trees (e.g. mango, papaya, etc.).

2.6. Community surveys

Community surveys were performed on the same day that observational data were collected, and were completed at each of the communities where physical and observational data was collected. We used a mixed methods approach, as has been used in other studies investigating water use and water infrastructure in Africa (e.g. Kosinski et al., 2016), with community surveys containing some quantitative and some open-ended qualitative data. In some cases, questions had defined categories, while in other cases the questions were open-ended and answers were categorized later. The interview tool was field tested during the intensive 2 day project training workshop held for the three NGO staff (SASOL, UDO, MCC) and four student interns (regional residents, who were from local Kenyan universities), and adjustments to interview questions were made.

Community surveys were conducted by the student interns who were native Kikamba (the local language) speakers. Questions were translated into Kikamba during the interview, and then answers were back-translated into English and recorded by the interviewer. See supplementary material for specific interview questions. Interviews were conducted as groups, since sand dams are generally viewed as a communal endeavor (Teel 2019), and answers therefore reflect a collective answer to the questions. Groups consisted of individuals who used and/or made and managed the dam, and were requested to answer on the basis of what they knew of perceptions and behaviors of the whole community. Interviews lasted about 30 min, and group size varied from 1 to 10 (with a median group size of 3). A lead spokesperson (female in 47% of interviews, median age 51) gave responses during the interview, with input from the other members of the group. Recorded answers were then coded for analysis.

3. Results

3.1. Potential water volume of sand dams

We estimated the theoretical amount of water stored in sand dams based on estimates of pore space of sediments and volume of sediment accumulated.

3.1.1. Sediment particle analysis

Particle analysis indicated a median particle size (D_{50}) of 440 μm, which falls in the medium sand category. Silt/clay, the size class of greatest concern, was a relatively small percentage in almost all samples (Table 2). Most particles were of fine sand or larger, which hold a larger amount of water, and which allow drainage of water through most of a sand dam's depth, based on depth-based calculations (Viducich 2015).

3.1.2. Calculated water volume

Calculation of potential available water in sand dams based on

Table 2
Particle size distribution in sampled sand dams.

	Average	Standard Deviation	Minimum	Maximum
Fine gravel (2000+ μm)	9.8%	5.6%	1.3%	25.4%
Coarse sand (500–2000 μm)	34.1%	11.2%	11.9%	68.9%
Medium sand (250–500 μm)	28.9%	8.0%	10.6%	51.8%
Fine sand (63–250 μm)	25.4%	9.9%	7.9%	59.8%
Silt/clay (0–63 μm)	1.9%	2.4%	0.1%	12.5%

measured sediment content, compared with this calculation if the sediment were entirely coarse sand, gives an estimate of the reduction in stored water due to siltation (presence of the smaller grain silt or clay). The reduction in stored water varied, but averaged between 10 and 25% (depending on whether low or high estimates of specific yield were used) (Table 1). Siltation therefore appeared to cause a relatively small decrease in water volume in most cases.

3.1.3. Watershed area and potential harvested volume

The total volume of sand dams varied by three orders of magnitude, from 34,000 L to 30,659,000 L. The majority of dams are skewed to the smaller end of this scale (median value of 949,500 L), with fewer dams having the notably larger volumes. Accounting for the measured sediment types, estimated median water volume was 144,200 to 302,800 L (for low and high specific yield estimates, respectively). At the recommended water consumption of 15 L per day per person for household consumption (Sphere Association 2018) (not counting livestock, irrigation or other uses), a median sized dam would support between 37 and 84 people for a four month period. Based on individual dam volume, 57% of dams would have enough water to provide four months of household water use to the reported number of beneficiaries (as reported by community surveys), if that were their sole source of water.

Watershed area collected by dams varied greatly, from 0.01 to 250 km^2 (Fig. 2), with a median area of 2.92 km^2. As a fraction of total rainwater falling in the watershed in the wet season (calculated from yearly average rainfall integrated for the watershed area), the amount of water stored by individual dams was very low. Median values for percent of the total watershed rain volume that were collected by individual dams were 0.05% and 0.03% in two wet season months (April and November, respectively), when calculated using the high estimate of specific yield. The maximum captured was 3.51% and 2.98% of total watershed rainwater in April and November, respectively.

3.2. Sand dam conditions and presence of water

3.2.1. Erosion

Evidence of erosion was present in the majority of dams, to varying degrees of severity. Slight, moderate, and severe erosion was noted in 22%, 25% and 21% of dams, respectively, with roughly equal erosion between the base and ends of the dam. No erosion was present in 28% of dams. Only 4% of the dams were broken and thus entirely nonfunctional in terms of holding sediments. A major issue with damaged or eroded dams is leakage of water from the dam. Evidence of possible leakage was present in 30% dams visited, as a single pool or multiple pools below the dam. As some dams showed no evidence of water in the sand bed, other dams may also be “leaky” when more water is present.

3.2.2. Sand filling and presence of water in sand

Of the dams that had not broken, 86% of dams were fully filled with sand (or other sediments). Another 11% of dams were half or three-quarters full, with only 2% empty or one-quarter filled. Although a few of the dams that were not fully filled were 2 or 3 years old, most were more than 3 years old, indicating that the lack of filling was not entirely due to the initial filling process of the dam.

Most (78%) of dams had water in the sand from at least some core samples, with 57% of dams having water in more than half of the core samples taken (Table 3). One third of all dams surveyed had water in all or nearly all (91–100%) of the sand samples taken from that dam, while 22% dams had no water in any of their samples, suggesting most sand dams are holding some extractable water. Deep coring presumably would have increased the percentage showing water even more.

3.2.3. Community self-reported water presence

When asked on community surveys how long water lasts in the dam, 39.5% of respondents reported water lasts for 4 months or more during the dry season, 37% reported water present for between 1 and 4 months, while 23.5% reported water was present for less than 1 month at the dam in the dry season.

3.3. Vegetation indices: NDVI and NDMI

For some dams, Landsat satellite analysis of vegetative greening and moisture confirmed what was observed in a more anecdotal manner on the ground–vegetative greening that was associated with the area immediately around the dam (Fig. 4A). In other cases, vegetative greening attributed to the dam was not immediately obvious (Fig. 4B). However, compiled satellite analysis indicated there was no statistical difference ($p > 0.05$; paired *t*-test) between the NDVI or NDMI at sand

Table 3
Percent of dams (N = 97) with water in core samples, categorized based on the percentage of core samples at that dam that had moisture.

Of core samples at a dam, percentage that had water	Percentage of the dams in category
0	22%
1–10	1%
11–20	5%
21–30	4%
31–40	2%
41–50	9%
51–60	3%
61–70	1%
71–80	13%
81–90	7%
91–100	33%

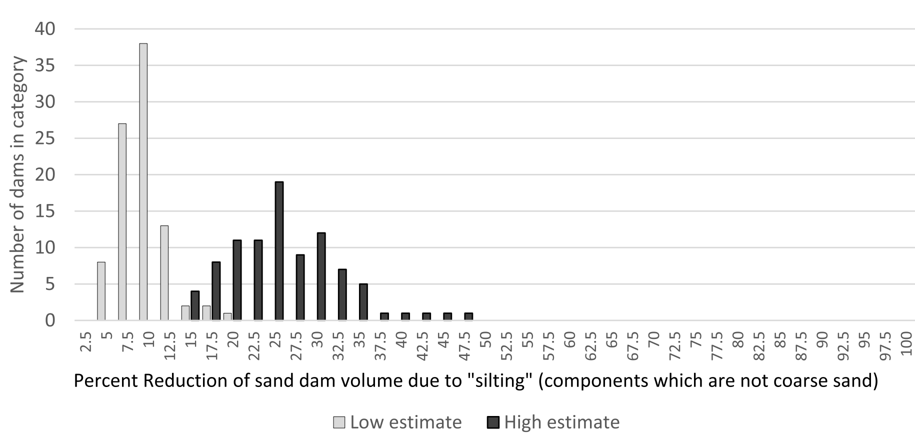

Fig. 3. Siltation effects on calculated sand dam water volumes, based on low and high specific yield estimates.

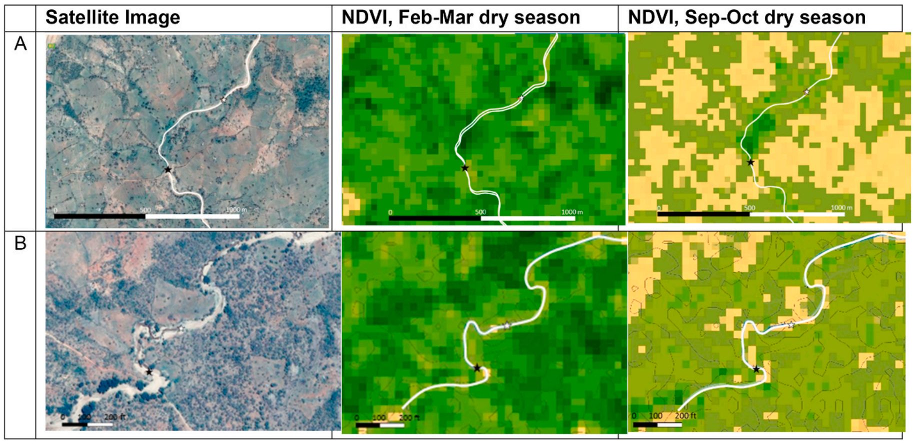

Fig. 4. Examples of vegetation index (NDVI) at sand dams, darker shades indicate more greening. Dam "A" shows obvious greening at dam site, while localized greening associated dam "B" is less obvious. White line is waterway, dark star is sand dam structure, white star is drawback. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

dam and control sites (200 m and 400 m distant) for either dry season (Table 4), regardless of whether the averaged area was close (within 30 m) to the waterway, or out to a greater distance (within 100 m). Thus, while there are individual instances of greening at dam sites that can be measured with satellite images, there was no evidence of consistent increase in vegetative greening or moisture at the dam sites. When core sample moisture were correlated against either NDVI or NDMI at individual dam sites, there was no relationship of water presence at dams with greening or moisture (all $R^2 < 0.02$). At both dam and control sites, NDVI and NDMI were higher when averaged within 30 m of the waterway, compared to when averaged out to 100 m, indicating that some greening and moisture was associated with the waterway regardless of whether a dam was present.

3.4. Water usage – observational data

3.4.1. Adjacent land use

Most land adjacent to dams (on average, 84% of land adjacent to a dam site) was bushland (including scrub trees, pastureland) and unused cropland (e.g. crops had obviously been grown in the past, but the land was currently unused) (Fig. 5). Evidence of benefits from sand dam in agriculture was seen in land use as vegetable fields and cultivated grass such as napier grass (6.3% of adjacent land), fruit trees (5%) and cropland with evidence of current use (5%). No active agricultural activities adjacent to dams were observed in 61% of dams surveyed, during the dry season when surveys occurred (Fig. 6). When present, there were more often multiple agricultural activities present at dams. Thus, communities that used dams for agriculture tended to practice a diversity of activities, but the majority of dams and adjacent land area was not used for agriculture. There was a small ($r^2 = 0.125$; $p < 0.05$) correlation showing an increase in the percent of adjacent land used for agricultural activities with the percent of sand samples with water.

3.4.2. Water harvesting

Evidence of active water extraction was observed in 43% of dams, while 18% of dams had evidence of past water extraction, and the remaining 39% of dams had no evidence of attempts to extract water. There was no difference in the percent of core samples showing water in dams with active water extraction vs those with no evidence of water extraction, but there were fewer core samples with water in dams with evidence of past water extraction (ANOVA with Tukey's post-hoc; $p < 0.01$). Of the dams where there was no evidence of water harvesting, 81% had evidence of water in the sand cores. Scoop holes were the most common water harvesting technique (Fig. 7). Open wells (permanent excavations with reinforced walls) were more common than pump wells, likely because of the expense associated with pump wells. Only 3 out of the 14 pump wells observed had water extraction, the remaining were either dry or broken.

Table 4
Vegetation index at sand dam compared with control sites at 200 m and 400 m from the dam structure (if downstream) or drawback (if upstream), analyzed close to the dam (30 m) or over a wider distance (100 m).

NDVI						
	30 m buffer			100 m buffer		
	Dam	Control, 200 m	Control, 400 m	Dam	Control, 200 m	Control, 400 m
Sept, Oct	0.1858 ± 0.0027 N = 87	0.1851 ± 0.0029 N = 87	0.1835 ± 0.0032 N = 80	0.1751 ± 0.0023 N = 87	0.1756 ± 0.0025 N = 87	0.1753 ± 0.0026 N = 80
Feb, Mar	0.2559 ± 0.0042 N = 86	0.2598 ± 0.0042 N = 86	0.2566 ± 0.0047 N = 79	0.2500 ± 0.0040 N = 86	0.2526 ± 0.0043 N = 86	0.2508 ± 0.0045 N = 79
NDMI						
	30 m buffer			100 m buffer		
	Dam	Control, 200 m	Control, 400 m	Dam	Control, 200 m	Control, 400 m
Sept, Oct	−0.0890 ± 0.0032 N = 87	−0.0897 ± 0.0035 N = 87	−0.0929 ± 0.0036 N = 80	−0.1029 ± 0.0027 N = 87	−0.1024 ± 0.0029 N = 87	−0.1039 ± 0.0031 N = 80
Feb, Mar	0.0080 ± 0.0050 N = 82	0.0077 ± 0.0049 N = 82	0.0056 ± 0.0057 N = 75	−0.0049 ± 0.0042 N = 82	−0.0029 ± 0.0051 N = 82	−0.0038 ± 0.0056 N = 75

Sample size (N) is number of dams; for each dam and each of the two dry seasons, NDVI and NDMI derived from satellite images from two separate years (in 2014–2017) was averaged to give an individual value for the dam and season.

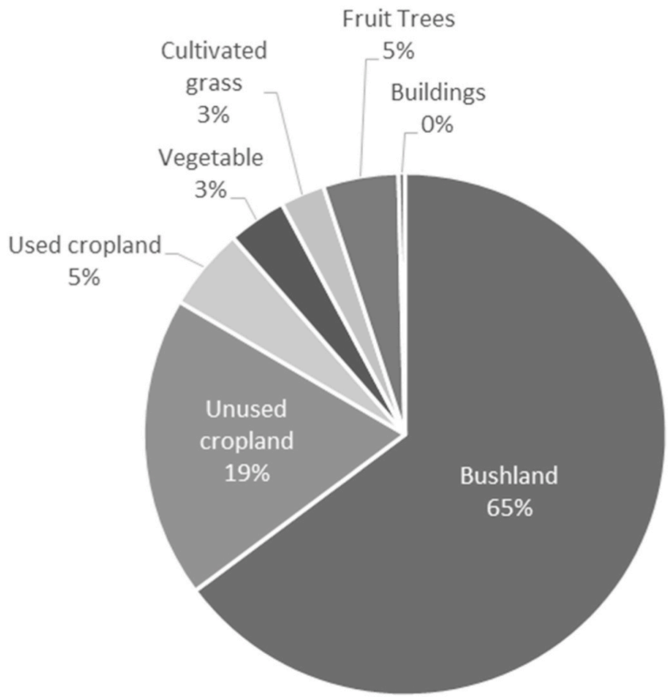

Fig. 5. Average percentage of land adjacent to sand dams dedicated to various activities. (N = 97 dams).

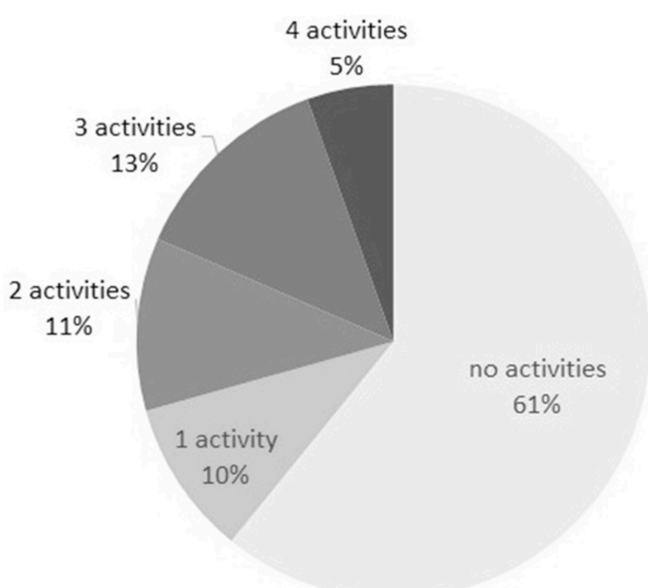

Fig. 6. Percentage of dams showing various number of agricultural activities on land adjacent to sand dams. (N = 97 dams).

3.5. Water usage - self-reported community surveys

3.5.1. Self-reported usage

When asked whether water from sand dams was used, 41.1% indicated it was the sole source of water, 21.1% indicated it was one of several sources, and 38.8% said it was not a source of water. Neither average percent water in core samples, nor average NDVI, differed between these three groups (ANOVA), indicating water presence was not the primary determinant of self-reported usage.

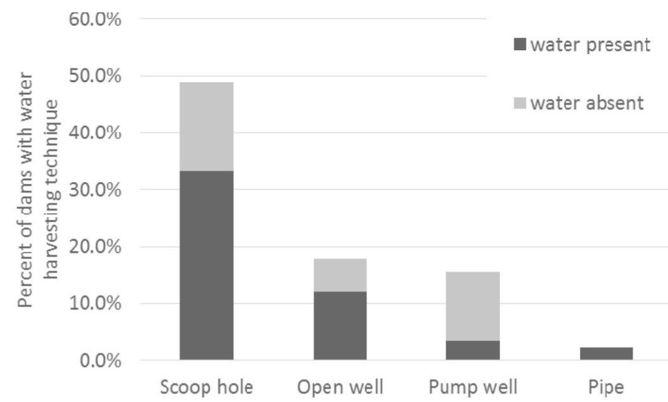

Fig. 7. Frequency of water harvesting techniques at dams (N = 97), indicating whether water was present or source was dry.

3.5.2. Sand harvesting

Most locations (88%) report that dams are used as sources of sand harvesting. Most dams where sand is harvested report that the entire community is allowed to harvest sand (90.4%), with the remainder restricting harvesting to group members (8.4%) or in one case to an individual. Sand harvesting was overwhelmingly for community use only; selling sand was only reported to be allowed at one dam site. However, selling sand is illegal and it is possible that any activities were not accurately reported by respondents. These results imply that sand dams provide a consistent benefit outside of water provision, and that there is some degree of group coordination of the sand dam as resource, since they have mutually agreed not to sell the sand. This management was not through highly formalized structures, as most dams (72%) did not have any reported formal management committee.

3.5.3. Benefits

Users readily report the expected range of uses of sand dams (interviewees were given the answer options for this question), with drinking/household usage most commonly reported as the primary usage (Fig. 8). The high percentage of dams reporting various primary activities does not match the lower percentage where water harvesting was observed (see section 3.4.2). Possibly respondents were reporting water use which has occurred at some period (but not necessarily at the time dams were visited). Alternatively, respondents were answering based on what they knew of potential uses of the water, rather than based on the actual past or present usage.

Groups were asked about how the benefits differed between men, women, girls and boys. These were open-ended questions which were subsequently categorized, and respondents were not prompted for the categories. For women, the largest benefit was clearly in saving time as they walk shorter distances to get water (Table 5). School attendance was cited most often for girls, but also to a lesser degree for boys. Girls are likely more involved with gathering water, and thereby benefit more

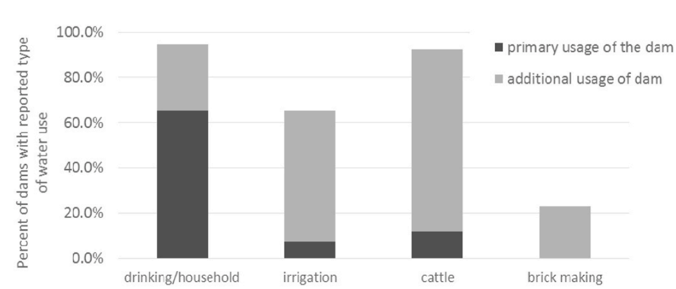

Fig. 8. Percent of dams (N = 97) reporting types of usage for water harvested from dam. Interviewed groups reported for all users of dam, listed all uses, and indicated the primary usage of water in the dam.

Table 5
Reported benefits of sand dams (N = 97), based on gender and general age. The top five items are shown for each category.

Women		Girls		Men		Boys	
Saves time/shorter distance	96.7%	Improved school attendance and performance	75.0%	Brick making/ construction	62.0%	Brick making/construction	46.7%
Improved health	42.4%	Improved health	51.1%	Livestock	51.1%	Income generation	37.0%
Income generation	13.0%	Brings unity/brings together	35.9%	Income generation	35.9%	Improved school attendance and performance	29.3%
Brings unity/brings together	5.4%	Saves time/shorter distance	32.6%	Irrigation	10.9%	Saves time/shorter distance	21.7%
Livestock	4.3%	Allows to sleep more	4.3%	Improved health	9.8%	Livestock	16.3%

from the dams. Benefits related to education included not only staying in school or increased attendance, but also improved performance as children could do their homework and were not tired during the day. In the absence of nearby water sources, children are reported to walk long distances at night, making children tired during the day. Improved health (e.g. through increased washing) was reported more often for women and girls, than for men and boys. For men and boys, activities around brick-making, livestock, and other income generation projects were reported most often.

4. Discussion

The range of parameters measuring water presence and use in this study confirm sand dams as a decentralized approach that can effectively provide water access – there was evidence of both the presence of water, and its actual use by adjacent communities at many of the sand dams. At the same time, there was highly localized variability in water access, especially with respect to the degree of water utilization. Sand dams were underutilized in many cases, and the results of the study point towards water use (for instance, social factors determining whether the resource is actually used), rather than water presence (for instance, physical factors impacting the actual accumulation and retention of water) as the more important determinant in explaining variability in water access at sand dams. These conclusions are generalizable to sand dams in general as the current study draws from a large sample size of sand dams which are broadly representative of the thousands of sand dams in Ukambani region of Kenya.

Sand dams in this study generally met the criteria for the potential storage of significant volumes of accessible water. Only 4% of sites had completely failed structures, consistent with Pauw et al.'s (2008) earlier report indicating complete breakage of only 5% of dams in Kitui. Furthermore, most dams (86%) were fully or nearly filled with sediments. Thus, the dams themselves were fundamentally robust structures, and had largely accumulated sediments as expected. A larger concern of sand dam structures has been the prevalence of erosion along the base or edges of the structure, which potentially reduces effectiveness by allowing water leakage out of the dam. Nearly a third of dams did have water below the dams, suggesting either leakage from the structure, or a raised aquifer extending around and downstream from the structure (Hoogmoed 2007). Design adjustments such as raising wings at the ends of dams have partially mitigated well-known erosion issues. In addition, organizations implemented many sand dams with accompanying terracing projects on adjacent land to reduce erosion that would into cause issues with siltation.

Dam functionality in terms of storing water is critically dependent on the particle size of the sediment which accumulates. Whereas water can be effectively extracted from the larger pore spaces in sand, water in silt and clay is more tightly bound in the small spaces, and is largely unavailable for extraction. Thus, several recent studies have questioned assumptions regarding storage volumes, on the basis of measurements showing extensive silting of sand dams which presents a barrier for recharge or water access (de Trincheria and Otterpohl 2018), and which can increase evaporation by drawing water to the surface through capillary action (Borst and De Haas 2006). Ponding of water on the dam surface is often observed in cases of surface siltation (Pauw et al., 2008; de Trincheria et al., 2015), which increases risk of disease through water contamination and breeding of insects.

Sediment analysis in this study confirmed the presence of some silt and clay, as indicated by particle analysis of core samples, and by general observation of sediment at sand dam sites. However, based on the analysis of particle sizes found at individual dams, compared with estimated specific yield in the sediment classes (Tables 1 and 2), we estimate that siltation reduced water storage by an average of only 10–25% (depending on the specific yield estimate used) (Fig. 3). Continued attention to the potential of siltation to limit sand dam function at specific sites is warranted, such as the role of watershed slope in determining sediment type, or the importance of staging of construction in low base flow situations (Gijsbertsen and Groen 2007; Viducich 2015). However, estimates in this study suggest that the efficacy of existing sand dams in Ukambani is not fundamentally compromised by extensive siltation.

We acknowledge that this is a simplified analysis of a complex hydrologic situation. For instance, we saw evidence of stratification, such as multiple silt layers which result from storm events (Johnson 1967). Although these can represent a small fraction of the total sediments, the layers could have a large impact by impeding water flow; we were not able to calculate magnitude of these effects. Such layers were observed by other studies in the region (de Trincheria and Otterpohl 2018; Quinn et al., 2019), occurring especially at low flow periods during the end of the rainy season (Viducich 2015). On the other hand, Gijsbertsen and Groen's (2007) detailed hydrological model of dams in the region suggested that turbulence suspends fine sediments in all but a small area behind the dam, and that dams with sufficient base flow (such as lower in catchments) maintain flushing of fine sediments that minimizes the impact of fine sediment layers. Second, we lacked sediment data from deeper in the dams due to the difficulty of sampling the full depth. However, we calculate that the depth sampled at dams covers 60% of sediment volume on average, and thus represents of a large portion of the storage volume of the dam. Third, our calculations are based on estimates of specific yield, which are difficult to estimate, especially for mixtures of particle sizes. Finally, we note that these are likely underestimates of available water, given that it does not account for water in the adjacent aquifer. Hydrological studies indicate that aquifers flows directly between the dam and aquifer (Hut et al., 2008; Quilis et al., 2009), in which case the aquifer is a reservoir than can effectively increase or decrease the volume of water stored by the dam (Quinn et al., 2019). When considered as part of the sand dam volume, several studies estimated the water in the aquifer represents a substantial portion of the total water in the sand dam (Borst and De Haas 2006; Jansen 2007). Others point to this effect as highly dependent on the specific dam and the sediment water permeability (de Trincheria et al., 2015; Quinn et al., 2019), underlining the difficulty in quantifying the role of the aquifer in sand dam volume.

The conclusions in this study that sand dams meet the criteria of having sufficient water storage potential is consistent with our field observations of the actual presence of water in dams. In the majority of cases (78%), water was observed in at least some sediment cores, even though cores generally did not extend to the deeper parts of the dams where water would be most expected. Water appears to be present in most of the dams in the dry season, as intended for sand dams. The majority (76.5%) of communities likewise reported that water lasted for at least 1 month during the dry season.

The calculated potential volume of water in most dams provides sufficient water for substantial periods of the dry season, consistent with the assessments of other studies (Aerts et al., 2007; Jansen 2007; Lasage et al., 2015). Although in some cases water harvesting can have negative externalities as water supplies to downstream communities are disrupted (Bouma et al., 2011), the volume of water collected at individual dams in this study was negligible compared to rainfall in the dam's watershed. Other studies likewise found that dams capture only a small fraction of the streamflow (Borst and De Haas 2006; Aerts et al., 2007; Lasage et al., 2015), although the impact would be significantly larger under changing rainfall patterns of climate change scenarios, especially if there is an increase in the number of dams built to meet the anticipated increase in water challenges (Aerts et al., 2007).

It is generally assumed that the accumulation of water at sand dams supports vegetative growth that would otherwise not be possible, an assumption that is clearly supported by anecdotal observations (e.g. Fig. 1). Surprisingly, extensive satellite analysis of sand dam sites across multiple dates during both dry seasons did not confirm this expectation. NDVI and NDMI (indicators of increased greening and general moisture content, respectively) were not consistently higher at dam sites compared to sites 200 m, or 400 m distant from the dam (beyond the 350 m extent of the dam-affected aquifer reported by Quilis et al., 2009). Neither was greening or moisture higher in dams with a higher prevalence of water in core samples. Given the large sample size, these estimates appear to be robust, but are difficult to reconcile with observations of water accumulated at sand dams and anecdotal accounts of vegetative growth at dams. Nor do they match the results of Ryan and Elsner (2016), who used NDVI measure to demonstrate an increase in vegetative greening during a drought period at four dams selected based on the accumulation of water, compared to control sites at a different watershed. Their results may be more indicative of the potential for sand dams to increase greening under specific conditions, whereas the results of this study draw from a broad sample of representative dams during more normal dry seasons. Undoubtedly vegetative growth is supported at some dams, but the extent of this effect appears to be more limited than was assumed.

These results indicate sand dams usually provide for the presence of water. Since current concepts of effective water access include water use indicators (e.g. Sustainable Development Goal 6; World Health Organization 2019), we estimated actual usage through a combination of observational and self-reported techniques. The majority of dams had some evidence of past or present water harvesting (61%), and many dams (39%) had evidence of some agricultural activities. Livestock manure was prevalent on dams, reflecting the role of dams in livestock watering, although this appears to have the negative side effect of significantly contributing to microbial contamination of water sources (Graber Neufeld et al., 2020). In addition to the main benefits of water storage, sand dams provide a critical resource in the sand itself, which was harvested for brickmaking by the vast majority (88%) of communities. Self-reported usage of sand dams was high (Fig. 6), suggesting that even if not currently used, some unused dams may have been more intensely used in the past.

Although this indicates that many dams clearly provide a benefit to communities, evidence of extensive water usage was less than expected. The majority of dams (61%) had no evidence of agricultural activities that are associated with water from sand dams (such as vegetable fields during the dry season), and transects indicate only a small percentage (16%) of total land next to sand dams had agricultural activities that depended on the sand dam. Cross-sectional analysis indicated a weak correlation of water presence with agricultural activities, and no association of water presence with self-reported water use, or observed evidence of water harvesting (see sections 3.4.1, 3.4.2, 3.5.1). Of the 39% of dams where there was no evidence of current or past water harvesting, a large percentage (81%) had water in the sand cores. These results indicate that a lack of water was not the main reason for an absence of water usage. This variability in water harvesting activities is consistent with other studies investigating the variety of specific benefits of sand dams, such as Cruikshank and Grover's (2012) extensive survey of social factors showing that in some cases a high percentage of community members reported some economic benefits, while in other cases a high percentage reported no economic benefits.

The community interviews in this study show that communities understood and valued the benefits of sand dams, even if those benefits were not always realized. Self-reported data indicates that the use of water for drinking and household purposes is most often seen as the primary benefit, and households (especially for women and girls) strongly value the reduced time required to collect water (Table 5), as is consistent with other assessments (e.g. Teel 2019). Communities identified a variety of important benefits (Table 5) which have been documented by other studies, such as increased income generation (Pauw et al., 2008), improved health (Lasage et al., 2008), and extended food security in the dry season (Rempel et al., 2005). Our survey highlights the gender specificity of benefits. Time savings, improved school attendance and performance, and improved health were most important to women and girls, while brickmaking, livestock watering, and general income generation were most important to men and boys. Also notable was the range of activities that communities understand as beneficial. Communities noted that there are indirect or more abstract benefits, such as a raised water table, or the facilitation of group activities and togetherness, and that benefits are not solely contingent on the presence of water, as sand harvesting itself was a prevalent activity.

In conclusion, the wide range of parameters in this study, combined with the large, representative sample of sand dams, supports the broad conclusions that 1) the majority of sand dams function as intended with respect to effectively collecting and storing water, but 2) the actual utilization of water from sand dams is less consistent. Although water access varied both in the degree to which water is present, and the degree to which it is used, the two factors were not strongly correlated indicating that the frequent underutilization of sand dams was not primarily due to absence of water. Community participation in construction of sand dams presumably encourages usage by community members, but participatory processes in rural water projects in the region do not always lead to a sense of ownership that would increase efficacy (Marks and Davis 2012). Post-construction support from government agencies or non-governmental organizations may also be critical to best ensure success, as has been demonstrated for rural water supply projects (Whittington et al., 2009; Marks et al., 2014). In addition, most communities (72%) in our study did not manage the sand dam resource through formalized structures, and it is possible that enhancing community coordination after the time of dam construction would increase usage rates of the dams (Cruikshank and Grover 2012).

CRediT authorship contribution statement

Doug Graber Neufeld: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Joseph Muli:** Conceptualization, Investigation. **Bernard Muendo:** Conceptualization, Investigation. **James Kanyari:** Conceptualization, Investigation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This project was supported by Mennonite Central Committee, Kenya, and sabbatical support from Eastern Mennonite University. There are no competing interests. The authors gratefully acknowledge the participation and support of UDO and SASOL in this study, and the helpful discussions with the many practitioners who work with sand dams in East Africa.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaridenv.2021.104472.

References

Aerts, J., Lasage, R., Beets, W., de Moel, H., Mutiso, G., Mutiso, S., de Vries, A., 2007. Robustness of sand storage dams under climate change. Vadose Zone J. 6 (3), 572–580.

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A., Stroosnijder, L., 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa–a review. Phys. Chem. Earth, Parts A/B/C 47, 139–151.

Borst, L., De Haas, S., 2006. Hydrology of Sand Storage Dams: A Case Study in the Kiindu Catchment, Kitui District, Kenya. MSc. Thesis, Vrije Universiteit, Amsterdam.

Bouma, J.A., Biggs, T.W., Bouwer, L.M., 2011. The downstream externalities of harvesting rainwater in semi-arid watersheds: an Indian case study. Agric. Water Manag. 98 (7), 1162–1170.

Cruickshank, A., Grover, V.I., 2012. "These are our water pipes—sand dams, women and donkeys: dealing with water scarcity in Kenya's arid and semi-arid lands. In: Leal Filho, W. (Ed.), Climate Change and the Sustainable Use of Water Resources. Climate Change Management. Springer, Berlin, Heidelberg.

de Trincheria, J., Nissen-Petersen, E., Walter, L.F., Otterphol, R., 2015. Factors Affecting the Performance and Cost-Efficiency of Sand Storage Dams in South-Eastern Kenya. Proceedings E-proceedings of the 36th IAHR World Congress.

de Trincheria, J., Otterpohl, R., 2018. Towards a universal optimization of the performance of sand storage dams in arid and semi-arid areas by systematically minimizing vulnerability to siltation: a case study in Makueni, Kenya. Int. J. Sediment Res. 33 (3), 221–233.

Gao, B.-C., 1996. NDWI—a normalized difference water index for remote sensing of vegetation liquid water from space. Rem. Sens. Environ. 58 (3), 257–266.

Gijsbertsen, C., Groen, J., 2007. A Study to Up-Scaling of the Principle and Sediment (Transport) Processes behind, Sand Storage Dams, Kitui District, Kenya. M.Sc. thesis. Vrije Universiteit, Amsterdam, p. 146.

Graber Neufeld, D., Muendo, B., Muli, J., Kanyari, J., 2020. Coliform bacteria and salt content as drinking water challenges at sand dams in Kenya. J. Water Health 18 (4), 602–612.

Hausner, M.B., Huntington, J.L., Nash, C., Morton, C., McEvoy, D.J., Pilliod, D.S., Hegewisch, K.C., Daudert, B., Abatzoglou, J.T., Grant, G., 2018. Assessing the effectiveness of riparian restoration projects using Landsat and precipitation data from the cloud-computing application ClimateEngine. org. Ecol. Eng. 120, 432–440.

Hoogmoed, M., 2007. Analyses of Impacts of a Sand Storage Dam on Groundwater Flow and Storage. M.Sc. thesis. Vrije Universiteit, Amsterdam.

Hut, R., Ertsen, M., Joeman, N., Vergeer, N., Winsemius, H., van de Giesen, N., 2008. Effects of sand storage dams on groundwater levels with examples from Kenya. Phys. Chem. Earth, Parts A/B/C 33 (1–2), 56–66.

Jansen, J., 2007. The Influence of Sand Dams on Rainfall-Runoff Response and Water Availability in the Semi-arid Kiindu Catchment. Kitui District, Kenya. M.Sc. thesis. Vrije Universiteit, Amsterdam.

Johnson, A.I., 1967. Specific Yield: Compilation of Specific Yields for Various Materials. US Government Printing Office.

Klisch, A., Atzberger, C., 2016. Operational drought monitoring in Kenya using MODIS NDVI time series. Rem. Sens. 8 (4), 267.

Kosinski, K.C., Kulinkina, A.V., Abrah, A.F., Adjei, M.N., Breen, K.M., Chaudhry, H.M., Nevin, P.E., Warner, S.H., Tendulkar, S.A., 2016. A mixed-methods approach to understanding water use and water infrastructure in a schistosomiasis-endemic community: case study of Asamama, Ghana. BMC Publ. Health 16, 322.

Lasage, R., Aerts, J., Mutiso, G.-C., De Vries, A., 2008. Potential for community based adaptation to droughts: sand dams in Kitui, Kenya. Phys. Chem. Earth, Parts A/B/C 33 (1–2), 67–73.

Lasage, R., Aerts, J.C., Verburg, P.H., Sileshi, A.S., 2015. The role of small scale sand dams in securing water supply under climate change in Ethiopia. Mitig. Adapt. Strategies Glob. Change 20 (2), 317–339.

Lasage, R., Verburg, P.H., 2015. Evaluation of small scale water harvesting techniques for semi-arid environments. J. Arid Environ. 118, 48–57.

Lin, M.-L., Chen, C.-W., Shih, J.-y., Lee, Y.-T., Tsai, C.-H., Hu, Y.-T., Sun, F., Wang, C.-Y., 2009. Using MODIS-Based Vegetation and Moisture Indices for Oasis Landscape Monitoring in an Arid Environment, 2009 IEEE International Geoscience and Remote Sensing Symposium. IEEE.

Marks, S.J., Davis, J., 2012. Does user participation lead to sense of ownership for rural water systems? Evidence from Kenya. World Dev. 40 (8), 1569–1576.

Marks, S.J., Komives, K., Davis, J., 2014. Community participation and water supply sustainability: evidence from handpump projects in rural Ghana. J. Plann. Educ. Res. 34 (3), 276–286.

Pauw, W.P., Mutiso, S., Mutiso, G., Manzi, H.K., Lasage, R., Aerts, J.C.J.H., 2008. An Assessment of the Social and Economic Effects of the Kitui Sand Dams. (IVM Report; No. R-08/08). Instituut voor Milieuvraagstukken.

Quilis, R.O., Hoogmoed, M., Ertsen, M., Foppen, J.W., Hut, R., de Vries, A., 2009. Measuring and modeling hydrological processes of sand-storage dams on different spatial scales. Phys. Chem. Earth, Parts A/B/C 34 (4–5), 289–298.

Quinn, R., Rushton, K., Parker, A., 2019. An examination of the hydrological system of a sand dam during the dry season leading to water balances. J. Hydrol. X (4), 100035.

Rempel, H., Nyaga, C.H., Manzi, H.K., Gaff, P., 2005. Water in the Sand: an Evaluation of SASOL's Kitui Sand Dams Project. SASOL, Kitui, Kenya.

Ryan, C., Elsner, P., 2016. The potential for sand dams to increase the adaptive capacity of East African drylands to climate change. Reg. Environ. Change 16 (7), 2087–2096.

Soil, K., 1996. Survey Laboratory Methods Manual, Soil Survey Investigations Report.

Sphere Association, S., 2018. The Sphere Handbook: Humanitarian Charter and Minimum Standards in Humanitarian Response. Geneva, Switzerland.

Teel, W.S., 2019. Catching rain: sand dams and other strategies for developing locally resilient water supplies. In: S, K., Bamutaze, Y., Singh, B., Nabanoga, G., Lal, R. (Eds.), Semiarid Areas of Kenya. Agriculture and Ecosystem Resilience in Sub Saharan Africa. Springer, Cham, pp. 327–342.

Tiffen, M., Mortimore, M., Gichuki, F., 1994. More People Less Erosion: Environmental Recovery in Kenya. John Wiley & Sons, Chichester, p. 311.

Viducich, J.M., 2015. Spillway Staging and Selective Sediment Deposition in Sand Storage Dams. Master's Thesis. Oregon State University, Corvallis, OR, USA.

Villani, L., Castelli, G., Hagos, E.Y., Bresci, E., 2018. Water productivity analysis of sand dams irrigation farming in northern Ethiopia. Journal of Agriculture and Environment for International Development (JAEID) 112 (1), 139–160.

Whittington, D., Davis, J., Prokopy, L., Komives, K., Thorsten, R., Lukacs, H., Bakalian, A., Wakeman, W., 2009. How well is the demand-driven, community management model for rural water supply systems doing? Evidence from Bolivia, Peru and Ghana. Water Pol. 11 (6), 696–718.

World Health Organization, 2019. Progress on Household Drinking Water, Sanitation and Hygiene 2000-2017: Special Focus on Inequalities. World Health Organization.