Assessment of Physical and Social Determinants of Sand Dam Effectiveness in Kenya

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Abstract

Sand dam effectiveness was assessed through a combination of physical and social parameters in a representative sample of 97 sand dam sites in Kenya. Sand dam structures at most sites (96%) were intact, although some erosion was observed at the majority (68%) of dams. 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 specific yield of the sediment. 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, sand dams in the region were therefore fundamentally 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. Community surveys report a high rate of sand dam use for drinking water and household use (94%), irrigation (65%), and livestock watering (92%). Sand dam users also report a large range of benefits which were highly dependent on gender– the most frequent benefit cited for women and girls was saving time for water gathering (97%) and increased school attendance (75%), respectively, whereas brickmaking/construction was the most cited benefit for both men and boys (62% and 47%, respectively). High self-report use rates were not matched by direct observation of activities at dams; only 43% of dams had active water harvesting present, and only 39% of dams had current agricultural activities that were due to the presence of the sand dams. This points towards a high level of community understanding of sand dam benefits, but a lower rate of actually realizing those benefits. These results suggest that continued attention to design features (such as reducing erosion and siltation) is important, but that opportunities exist for increasing usage through more attention to management of sand dams and support of the activities associated with the dams.

1. Introduction

Globally, 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 one of a variety of locally appropriate solutions 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, 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 (Woodring 2014, de Trincheria et al. 2015, Viducich 2015, de Trincheria and Otterpohl 2018). In other cases, the questions center around whether effectiveness has been hindered by the lack of appropriate social structures (Cruikshank 2010). Historically, 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 the physical and social parameters that determine effectiveness of sand dams as a tool for improving livelihoods of communities in water-scarce regions. 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.

Fig. 1. Two examples of sand dams in Ukambani. Sand dam in left panel has intact dam face, functional scoop holes for water collection (in background, 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.

2. Methods

2.1 Sand dam selection and survey 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 collecting 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, 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.

Locations of the sand dams randomly selected for this survey tended to be clustered in certain regions (Fig. 2). This reflects not only population centers, but also the practice of many communities building multiple dams. All areas had the same distinct dry seasons (Jan-Mar; Aug-Oct) and wet seasons (Apr-July; Nov-Dec). Surveys were conducted in the dry seasons of 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).

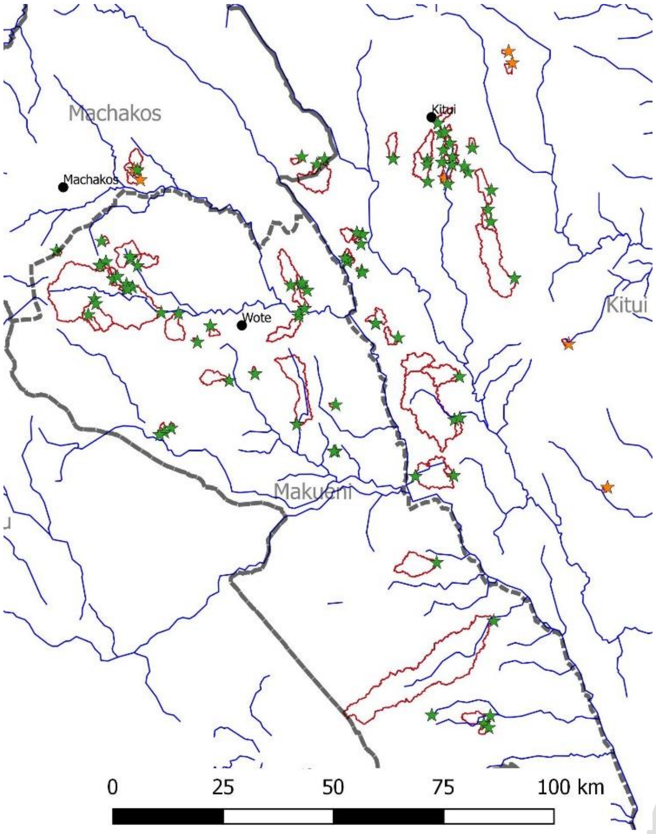

Fig. 2 Location of sand dams that were surveyed, relative to major waterways and county boundaries. Sites in green are UDO and SASOL dams. Sites in orange are colonial-era dams. Watershed areas draining into the sand dams are shown in red outlines.

2.2 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.

2.2.1 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 1.5m. 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 0.7m. 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 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 minutes, in order to separate sediments into broad size classes (0-0.063 mm, 0.063-0.250, 0.25-0.5 mm, and >0.5mm), 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 usable water content of sediments varies according to the size of the particles (usually expressed as particle radius in microns), with smaller particles having lower usable water content. The actual amount of usable 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 "usable" or "extractable" water) in standard particle size classes. (Johnson 1967)

particle size (microns)		Estimated usable 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 usable 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 usable water due to the presence of the smaller particles.

2.2.2 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 to 50 meters (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 meters, for instance), and we estimated the location of an approximate transition from the dam to the unaltered river bed.

2.2.3 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.

2.3 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 200m and 400m distance from the sand dam, based an estimated zone of groundwater influence of 350m (Quilis et al. 2009). Data were integrated in a 30m and 100m 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 400m 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 30m.

2.4 Observational Data

Observational data was collected for land assessment for evidence of water harvesting, including use of land adjacent to sand dams. Any evidence of use of water use was recorded, such as scoop holes (used or unused), open wells, and the presence of water pumps or other equipment. Land use was assessed in transects to an estimated 30 m laterally from the dams, at 15-50m intervals (depending on the size of the dam), as a means of quantifying agricultural uses of the land near dams. 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.).

2.5 Community Surveys

Community surveys were conducted by native Kikamba (the local language) speakers, and answers were recorded in English. 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 were made 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. In some cases, questions had defined categories, while in other cases the questions were open-ended and answers were categorized later. Interviews lasted about 30 minutes, 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.

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).

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%

3.1.2 Calculated water volume

Calculation of potential available water in sand dams based on 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 10-25% (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.

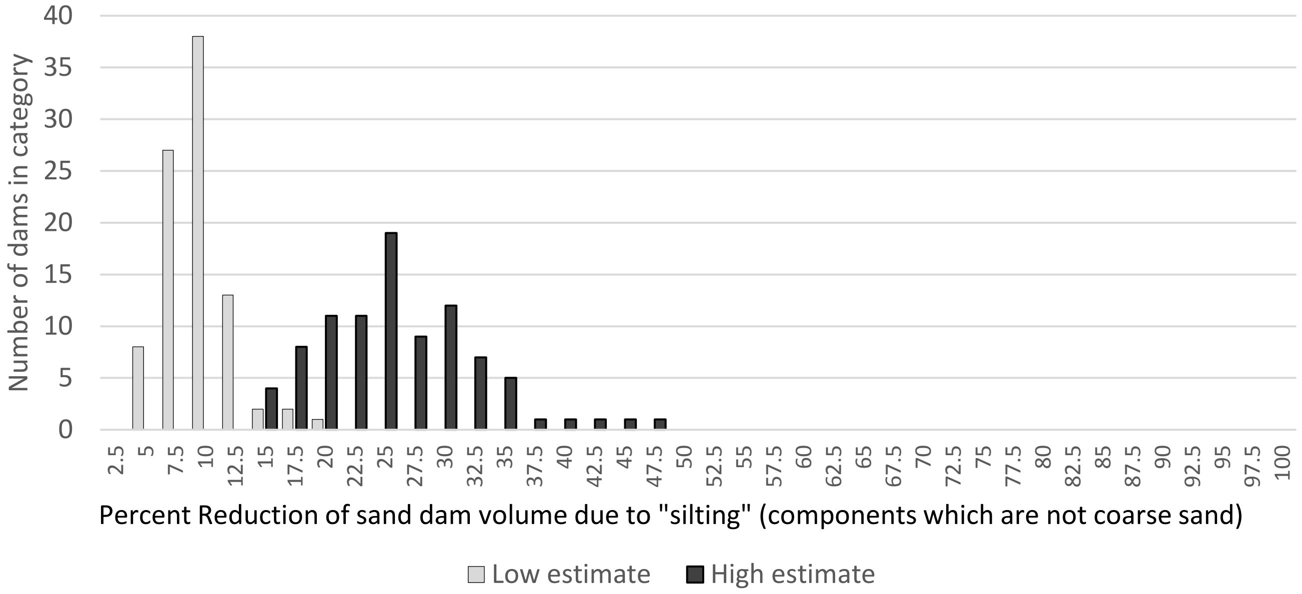

Fig. 1. Siltation effects on calculated sand dam water volumes, based on low and high specific yield estimates.

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 15L 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 to 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.

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%

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 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 30m) to the waterway, or out to a greater distance (within 100m). 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 30m of the waterway, compared to when averaged out to 100m, indicating that some greening and moisture was associated with the waterway regardless of whether a dam was present.

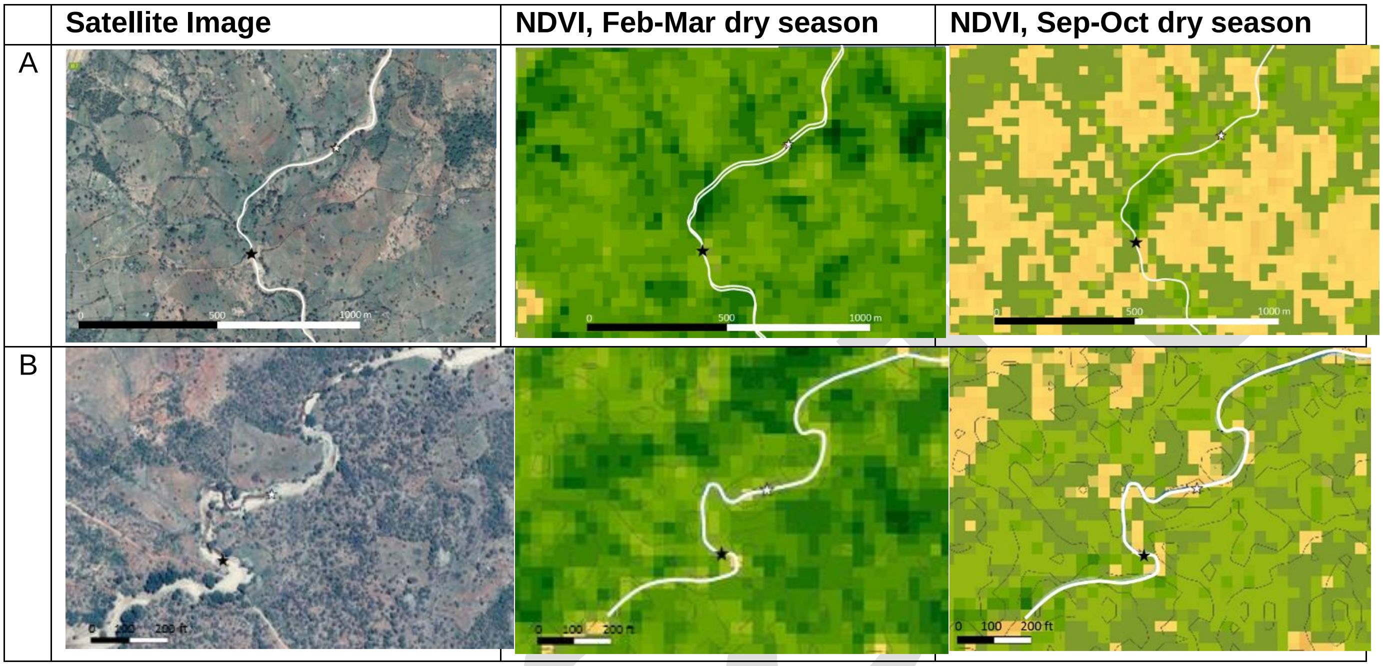

Fig. 4 Examples of vegetation index (NDVI) at sand dams, darker shades indicate more greening. Dam "A" shows obvious greening at dam site, while localized greening associated dam "B" is less obvious. White line is waterway, dark star is sand dam structure, white star is drawback.

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

NDVI						
	30 m buffer			100 m buffer		
	Dam	Control, 200m	Control, 400m	Dam	Control, 200m	Control, 400m
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, 200m	Control, 400m	Dam	Control, 200m	Control, 400m
Sept, Oct	-0.0890 ± 0.0032	-0.0897 ± 0.0035	-0.0929 ± 0.0036	-0.1029 ± 0.0027	-0.1024 ± 0.0029	-0.1039 ± 0.0031

	N=87	N=87	N=80	N=87	N=87	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.

3.4 Evidence of usage

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.

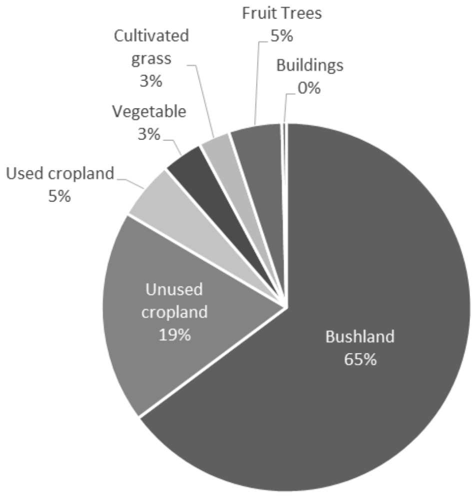

Fig. 5. Average percentage of land adjacent to sand dams dedicated to various activities. (N=97 dams)

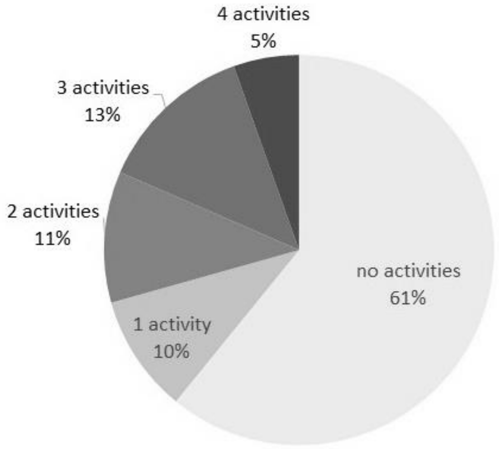

Fig. 6. Percentage of dams showing various number of agricultural activities on land adjacent to sand dams. (N=97 dams)

3.4.2 Water harvesting

Active water extraction was observed in 43% of dams, and 18% of dams had evidence of past water extraction (sources presumably had since dried). In the remaining 39% of dams, there was no evidence of attempts to extract water. 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.

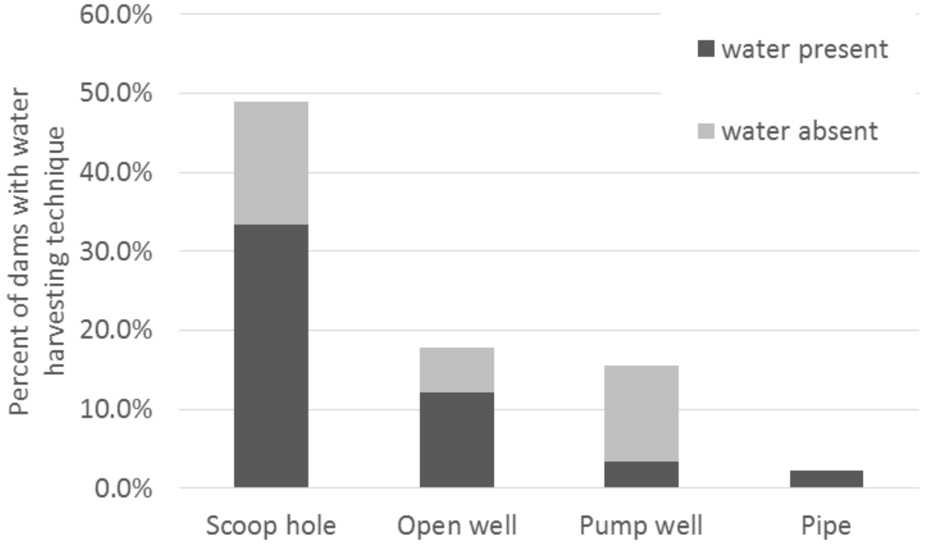

Fig. 7. Frequency of water harvesting techniques at dams (N=97), indicating whether water was present or source was dry.

3.5 Self-reported Community Surveys

3.5.1 Usage

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.

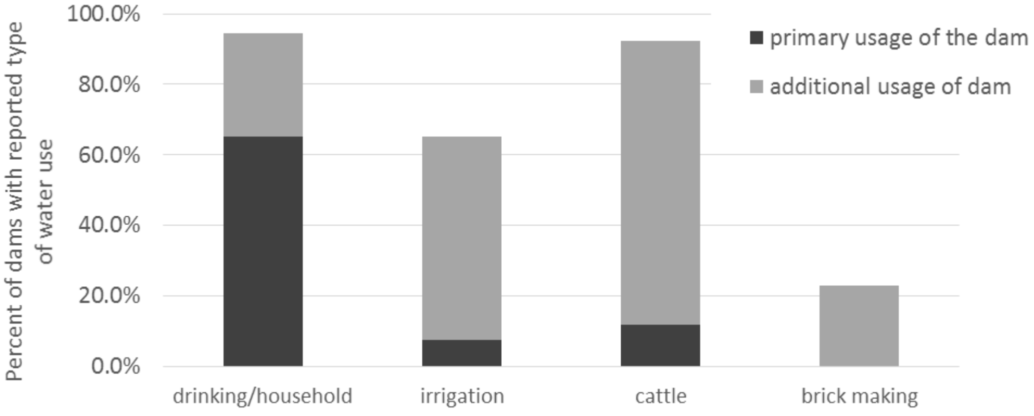

Fig. 8. Percent of dams (N=97) reporting types of usage for water harvested from dam. Interviewed groups reported for all users of dam, listed all uses, and indicated the primary usage of water in the dam.

3.5.2 Benefits

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 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.

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%

3.5.3 Dam management and sand harvesting

Most dams (72%) did not have any reported formal management committee, and 90% of dams reported there was no “conflict” (possibly interpreted as serious conflicts). Communities therefore usually did not manage the sand dam resource through highly formalized structures. 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 this resource as they have mutually agreed not to sell the sand, despite the lack of formal management.

4.0 Discussion

The range of physical and social parameters assessed in this study confirm the potential benefits of sand dams, while pointing towards highly localized variability in the realized benefits, and underutilization in many cases. The results of the study point towards social factors (those determining the frequency that the resource is actually used), rather than physical factors (those impacting the actual accumulation and retention of water) as the more important determinant in observed explaining variability in sand dam effectiveness. 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 1,2), 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). 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 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.

The physical assessment thus suggests sand dams are sufficiently functional to provide water, but water from the dam must also be effectively utilized by the community in order to judge the sand dam as effective. 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 (Neufeld et al. 2019; in revision). 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 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. 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. This suggests that an absolute lack of water was not the only reason for an absence of water harvesting. Overall, the combination of obvious but inconsistent presence of water harvesting in sand dams points towards a high degree of variability in realizing the benefits of sand dams. This is consistent with other studies investigating the variety of specific benefits of sand dams, such as Cruikshank's (2010) 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 suggested 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 (Woodring 2014, 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 (Woodring 2014). 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 harvesting itself was a prevalent activity.

The frequency of self-reported usage is higher than what is noted based on observational data; we suspect this reflects a combination of reporting past activities that are no longer being practiced, as well as reporting general knowledge of what is understood as the potential or aspirational benefits of sand dams. This highlights the general difficulty of collecting accurate data on sand dam usage and benefits, and the caution needed in interpreting any community survey data, as is commonly recognized in other sectors such as water sanitation (Contzen et al. 2015).

Taken as representative of the larger sand dam endeavor in Ukambani, the combination of parameters measured from a large, representative sample of sand dams in this study points to a wide variation in sand dam efficacy which is highly dependent on specific context. Most dams would not be considered either “optimal” (ample water throughout the year and robust usage by the community) or “failures” (little capacity for water storage and/or largely unused), but rather fall in the “moderate efficacy” category. As most dams seemed capable of retaining usable water, variation in efficacy appears more correlated with the social aspects of sand dam function. 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 2010).

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