Review of Literature on Sand Dams
Sept, 2015; Doug Graber Neufeld

General Background

This is a brief review of available published literature as of September 2015, with a focus on 1) academic articles, 2) organizational reports (e.g. reviews by MCC), and 3) manuals which outline practical technical and social aspects of sand dam implementation. Popular summaries (e.g. organizational pamphlets) were not reviewed, as they generally attempt to summarize what is published in other studies, or what is anecdotally known by the organizations. The document focuses on technical aspects, such as hydrology, soil, geology, and agriculture, in addition to summarizing some of the known direct and indirect costs and benefits. Less emphasis was placed on reviewing literature related to how self-help groups run, community organizing, and some of the other social aspects of sand dams. The observations do not include extensive discussions with the organizations or other stakeholders, and likely missed some published resources. However, the literature was read with enough attention to provide some objectivity based on the more rigorous assessments which have been published.

Although there are instances of sand dams, or sand dam-like technology, being used at various locations around the world through history, its occurrence in Kenya is relatively recent (first accounts being near the end of the colonial period). None-the-less, there is a rich history surrounding the sand dams in Kenya, and Kenya likely now has the largest concentration of sand dams in the world. This large number of sand dams in the countries has garnered international attention. In addition, key personalities and organizations have been instrumental in popularizing sand dams (e.g. accounts by Wayne Teel[1]). Cultural aspects of some Kenyan communities, such as familiarity with communal projects, seems to lend itself to the nature sand dam implementation. For instance, there is a tradition of self-help groups that lends itself to the close cooperation required for successful sand dam implementation.

Sand dams require a relatively large initial investment of resources, but then require relatively little ongoing maintenance. Material costs per dam run ~$8000[2], and many communities have multiple dams. Investment in dams therefore run around $30,000 per community[3]. Costs are provided by organizations or sponsor companies; communities provide the labor for construction. In a sense the dams are therefore not considered sustainable as their implementation requires ongoing external inputs.[4] Most organizations have used this community paradigm in promoting sand dams. In other cases, sand dams have been associated with road crossings[5].

Sand dams are technologies which are not applicable to all situations—on this there is agreement, even if there is disagreement on when exactly they are appropriate solutions. Aside from needing a particular social context (e.g. a community which can sufficiently agree and work together on the project), specific engineering criteria must be met. Sand dams are highly dependent on specific conditions, such as soil characteristics, topography (e.g. slope), and underlying bedrock, which primarily provide for optimal water flow and source material to ensure dams are filled by coarse sand rather than silt or clay. These conditions are found in much of Machakos and Kitui—collectively known as the Ukumbani region.[6] Bedrock in the region is low-permeability metamorphic (e.g gneiss)

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[1] Teel, 2011, Teel "Water Scarcity…"

[2] Woodring 2014, de Trincheria et al 2015

[3] Woodring 2014

[4] ibid

[5] Neal 2012, Woodring 2014

[6] Kasperson et al 1995, Jansen 2007, Teel "Storage Capacity…"

rock which hinders the formation of large aquifers, although cracks in the bedrock probably provide storage or access to water stores. The parent material is also critical for providing the source material for coarse sand to fill the dam; where there is granite, sandstone and quartzite in the region, coarse sand is most available.[7]

The Ukumbani region suffers from high erosion, partly due the history of its development during the colonial and post-colonial period[8]. Soils are generally poor, although some areas are relatively fertile. Some areas consist of black cotton soils which complicate the implementation of sand dams.[9] Overall these characteristics result in the region historically suffering from poverty and periodic famine. Historically, rainfall occurs primarily in the two wet seasons. Rainfall amounts can be substantial (e.g. about 1 meter per year in one area) but high evaporation (1.5 m per year in the same area) and rapid runoff (water rapidly runs off the soil rather than infiltrates) result in water deficits for much of the year.[10] Rains fail regularly (about 1 out of 4 years), and there is meteorological evidence for long-term changes associated with climate change, including an increase in frequency of dry years.[11]

Engineering and Hydrology

Sand dam performance (in terms of quantity of usable water stored) depends on several key factors:

Landscape Slope and Catchment position.

The steepness of the surrounding hills can have a large impact on dam performance, with optimal slope of about 1-4%[12]. Steeper sloped catchments may not provide sufficient infiltration[13] and result in finer sediments[14], while shallow slopes more likely have topography that is not optimal for a constrained dam (i.e. broad riverbeds make dams unmanageably long and make it more difficult to keep water flow from going around dams). Riverbanks should be high enough that the dam size is not unreasonably large.[15] Sites located in catchment headwaters are considered suboptimal. Gijsbertsen emphasized the importance of these aspects his GIS study[16], where he correlated the nature of sediment mobilization, transport and settling. For instance, smaller drainage of the catchment headwaters where considered insufficient for the higher water flow needed to wash out silt and clay particles from behind the dam.

Source Material

The source material that will fill the dam varies with geology, soil and weather conditions. It is critical that sufficient coarse sand is available to fill the dam area, so that maximal water pore space is available for water storage and use. Gijsbertsen concluded that most material comes from the riverbanks and is mobilized during the rising phase of a storm event[17]. Nissen-Petersen, however, suggests that most source material comes from the broader catchment basin, and that intensively farmed basins produce finer sediments than basins dominated by

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[7] [see Viducich 2015]

[8] Tiffen et al 1994 give a good overview of regional history

[9] Gijsbertsen 2007, Pauw et al 2008

[10] Borst and de Haas 2006, Lasage et al 2008

[11] Lasage et al 2008

[12] Gijsbertsen 2007, Hut et al 2008

[13] Gijsbertsen 2007

[14] Viducich 2015

[15] Teel “Storage capacity…”

[16] Gijsbertsen 2007

[17] Ibid

rocky outcroppings[18]. Granites, quartzite and sandstones are more favorable source materials than rhyolite or basalt.[19]

Bedrock permeability

Dams should be built on bedrock for stability of the dam and to keep water from seeping out of the sand which accumulates behind the dam. However, Gijsbertsen[20] noted that some advocate building on tight clays that may be an advantage in preventing water from leaking through bedrock cracks.

Presence of an Aquifer and its Characteristic

In principle, water from the dam should infiltrate the surrounding area to increase the surrounding water table[21]. This water is “useful” water in as much as it supplies vegetation on land adjacent to rivers, and also feeds water back into the sand dam later in the dry season. It could also support water supply in shallow wells located on the river banks. There is some disagreement as to the presence or extent of aquifers and their importance; see later in this document for a more detailed discussion of this aspect of sand dams.

Water Quantity

The efficacy of sand dams depends firstly on the quantity of water stored by the dam—adequate performance of the dam is necessary (but not sufficient) for communities realizing benefits of the sand dam. Other factors are key, such as cooperation among community members, dam resilience and water quality, with specific goals for the dam determining the specific ways these needs must be met. The centrality of water quantity, however, has resulted in multiple studies attempting to measure or model water volume. These studies attempt to extend the anecdotal or self-reported increase in water volume and water table near sand dams.[22] Such studies are critical for establishing whether the anecdotal accounts of large water volumes (e.g. enough to last throughout dry seasons) are accurate and generalizable. For instance, undoubtedly many communities utilize large quantities of water that are harvested by the dams, but rigorous studies can help establish what design principles maximize volume stored (e.g. topographical or geological features), or can help guide what uses can be supported by a particular dam (e.g. whether large volumes of water pumped for irrigation are sustainable). Several Dutch studies have given particular attention to this aspect of sand dams.

The volume of water stored can be conceptualized as two compartments – the riverbed sand itself, and the riverbank. Within each compartment, the volume of water stored depends on the volume of the compartment, and the nature of the material within that compartment (e.g. coarse sand vs silt in the riverbed). The volume in the riverbed compartment is perhaps the most straightforward measurement, volume can be measured using surveying equipment, or estimated by assuming an “average” geometry of the riverbed and applying this across the length and breadth of the storage area[23]. Calculated water volumes held in sand dams are generally around 500-2000 m^3.[24] These calculations assume coarse sand throughout the dam volume, an assumption that is contested by some (see discussion below). It also depends on the value used for specific yield (the fraction of volume which has accessible water); this should not be confused with porosity, which is a higher value[25] but includes interstitial water which is tightly bound and effectively inaccessible. Finally, finer sediments accumulate

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[18] [see Viducich 2015]

[19] ibid

[20] Gijsbertsen 2007

[21] Aerts et al 2007, Hoegmoed 2007

[22] Pauw et al 2008

[23] Teel “Storage capacity…”

[24] Hoegmood 2007, Hut et al 2008, Borst 2009, de Trincheria et al 2015, Lasage et al 2015

[25] e.g. see values referenced by Viduvich 2015

organic material more easily and support vegetation growth, resulting in evapotranspiration loss.[26] In principle the amount of actual siltation can be measured in dams, but in practice this has rarely been done. de Trichineria et al measured this in their study, and found significant fine sediment buildup at lower levels of a set of dams in southern Kitui.[27] Viducich measured this for dams in a broader area and found less evidence of siltation. Others (e.g. sand dam organizations) undoubtedly have observed the degrees of siltation in sand dams, and users who dig scoop holes would have some idea of this as well. To date, however, there is no broad systematic survey on effects

The location of fine sediments is also important, at least for thicker aquifers, fine sediments are less critical near the surface.[28] The particular gradient of particles may have a larger impact than realized, thin layers of fine sediments could influence the overall flow of water in different ways depending on location. Thus, it would be helpful to follow up on the siltation measurements and models to get a more comprehensive picture of this parameter.

The volume on riverbanks available for water storage, and the nature of the material in this area, is harder to assess. Despite the difficulty in measuring groundwater, most studies conclude that there is the potential for substantial groundwater storage that contributes to the volume of water available from sand dams. Estimates of water in such an aquifer vary. In reality, the extent of this would depend on a number of factors. In many cases there likely is no aquifer initially present, and the bedrock may be shallow enough to hinder the development of a substantial aquifer adjacent to the dams. The depth of the overlaying unconsolidated rock and soil is critical for determining the extent of water stores along the banks. The particular characteristics of an aquifer would also vary depending on the hydrologic conductivity of the material – estimates vary from a slow 9 mm/day[29] to 1-10 m/day[30]. At the slower rate, the aquifer level would take multiple years to raise to a stable level—models show water levels continuing to increase after 9 years.[31] de Trincheria et al argued that low conductivities effectively prevent riverbank aquifers from being a source of usable water, and are critical of including this groundwater in estimates of sand dam volumes.[32] Orient Quillis et al used piezometers to measure aquifer response more directly, and found that subsurface water on the river banks responds quickly to dams filling.[33] Hut et al note that infiltration will be strongly dependent on the nature of water use; the use of large amounts for irrigation (for instance, by pumping) would likely prevent effective recharge of the water table near the rivers.[34]

From these empirical and modeling studies, various volumes have been estimated for the quantity of groundwater around sand dams. Borst estimated that 40% of water captured by sand dams is within this aquifer, rather than in the sand itself[35], while Jansen estimated around 75%.[36] Exact quantities of water in the aquifer likely vary considerably due to the nature of the soil and geology, in addition to dam height (relatively small changes in dam height can have relatively large effects on groundwater[37]) and extent of groundwater flow around the dam. Water clearly accumulates downstream from dams, this may indicate a loss of water downstream

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[26] ibid

[27] de Trincheria et al 2015

[28] ibid

[29] Hut et al 2008

[30] Orient Quillis et al 2009, see Viducich for refs on typical permeability of sand

[31] Hut et al 2008

[32] de Trincheria et al 2015

[33] Orient Quillis et al 2009

[34] Hut et al 2008

[35] Borst and de Haas 2006

[36] Jansen 2007

[37] Hoogmoed 2007, Borst and de Haas 2006

through groundwater flow[38], or a failure in dam design that allowed for "leakage", particularly if no natural aquifer is present[39]. Alternatively the downstream increase in water might be viewed as additional storage of usable water (for use from scoopholes, or benefiting nearby land via the aquifer)—an expansion of the "zone of influence" for the dam.[40]

In total, the volume of water in the riverbed and riverbanks combined has been estimated up to around 5000 cm^3. This matches estimated water usage for the dry seasons (2400-3400 m^3).[41] Probably this represents a potential which is realized in some cases but not others. What proportion of dams match this potential is not established, and is in need of clarification. In brief, both models and field measurements point towards a system that *can* provide substantial water in the dry seasons, but that is highly depend on the specific conditions and thus *may not* provide substantial water in some conditions. This points to understanding sand dams as a technology that is appropriate under some situations, but that sand dams will not perform to expectations if certain conditions are not met. This highly general statement is not contentious in itself—the debates center around the specifics of when and where dams are functional, and the overall (program-wide) cost effectiveness of the technology as currently practiced (see below).

Failed and Suboptimal Sand Dams

Not all sand dams perform to expectations. Technical failure of sand dams (vs organizational failure, such as a community failure to manage water rights) is primarily for two reasons: 1) structural failure of dams occurs if they aren't properly constructed—for instance some dams with inadequate wings failed as the channel cut around the dam, and 2) more often, sand dams fail because of siltation as fine sediments prevent storage and access of water.

Dam structural failure was found to have occurred in 10% of cases in one study[42], most of which was attributed to erosion caused by increased farmer activities on the riverbank. Foundational erosion could also occur as turbulence downstream of the spillway erodes the base[43], although this is likely not a sand dam issue per se, but rather a general phenomenon of poor dam construction[44]. In some cases, such as when there is deeper bedrock, communities have reported to "shortcut" the construction process and not dig deep enough to site dams directly on the bedrock.[45]

Others report higher sand dam non-functionality due to siltation: one report anecdotally estimates 40% of dams nonfunctional[46], while Nissen-Peterson has claimed up to 90% of dams built are no longer functional[47]. Viducich concludes a failure rate of around 50%. Failure of a sand dam need not be permanent, Viducich notes the possibility of rehabilitating dams, something which to date apparently has not been attempted.[48]

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[38] Hoogmoed 2007

[39] de Trincheria et al 2015

[40] Hoogmoed 2007

[41] Aerts et al 2007, Borst and de Haas 2006, [cited to Alvarado 2006, have this article??]

[42] Pauw et al 2008

[43] Nissen-Petersen 2010

[44] Maddrell 2014

[45] [Rempel? Teel? – this was on in one of the reports where interns observed this in dam construction]

[46] Viducich 2015

[47] Nissen-Petersen 2010

[48] Viducich 2015

The actual prevalence of silt and/or clay accumulation, as opposed to the coarse sand needed for functioning sand dams, is a major outstanding question. Several authors have recently questioned assumptions regarding storage volumes, on the basis of measurements which show extensive clogging of pore space in sand dams. Although silt and clay does contain extensive pore space, water is tightly bound in the small spaces and is largely unavailable for extraction.[49] Finer particles also increase evaporation due to higher capillarity—water is draw to the surface where evaporation occurs much more rapidly.[50] Nissen-Petersen noted a 1.5 meter deep sand dam that had coarse sand in the top and bottom layers, but most of the middle consisted of soil and silt.[51] Only the top 0.2 m of that dam consisted of pure sand. Thus, he concluded the dam had low effective storage capacity.

The sharpest critique of sand dam performance was offered by de Trincheria et al, who extensively studied 30 dams in Makueni[52], the same region cited by Nissen-Petersen. They note extensive siltation in these dams; of critical note is that coarse sand covered a shallow layer on most of these dams making it appear that they were more effective than they were (most of the region below the shallow sand layer was silted). Silt wedges are reported by Viducich, occurring especially at low flow periods during the end of the rainy season.[53] Surface fine sediments are often washed away in subsequent storms, but bottomset beds of silt may remain. Visible ponding of (stagnant) water is reported in studies, consistent with possible siltation issues.[54] Siltation causes water to pond on the surface, likely increasing water contamination and allowing insects to breed (increasing disease risk), and increasing water loss via evaporation.[55] de Trincheria et al have most directly challenged the general cost-effectiveness of sand dams based on these issues (see below).

Central to the issue of siltation is the degree to which it is necessary to build a dam in stages, and a variety of recommended heights have been promoted to avoid siltation[56]. Sand dams take a variable time period to mature (fully fill with sand). Filling occurs upstream first; this occurs water flowing toward the dam drops its sediments as velocity slows. A ridge forms some distance upstream from the dam, over which water velocity is higher. Downstream of the ridge, velocity drops, and sand drops out downstream from the ridge. The ridge thus moves forward towards the dam until the dam is filled with sand.[57] Single-stage higher dams can have a greater initial pooling of water in front of the dam and drops fine sediment rather than just coarse sand. At least in situations where flow rates are lower and fine sediment loads are higher, building consecutive stages can thus limit fine sediments by ensuring that flow rates are always high enough to wash away fine sediments. Thus, de Trincheria et al strongly argue for building dams in stages in all cases, citing others who recommend various limits the height of stages.[58] In particular they note building the dam in stages is a “precautionary principle” approach which avoids the risk of siltation where the exact performance of the dam cannot be predicted.

Others argue that hydrodynamics behind dams are generally sufficient to wash out fine sediments even when the dam is initially high. For instance, Gijsbertsen did a detailed hydrological model suggesting that turbulence suspends fine sediments in all but a small area behind the dam. Gijsbertsen noted that sediment transport occurs during the rising limb of a storm event; subsequent base flow is responsible for flushing out fine sediments. Fine sediments take several hours to settle, and form a loose crust that is readily washed away by base flows. He

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[49] Nissen-Petersen 2011

[50] Borst and de Haas 2006

[51] Nissen-Petersen 2011

[52] de Trincheria et al 2015

[53] Viducich 2015

[54] Rempel et al 2005, Pauw et al 2008, de Trincheria et al 2015

[55] see Pauw et al 2008

[56] see table 2.3 in Viducich 2015

[57] Gijsbertsen 2007

[58] de Trincheria et al 2015

concludes that dams lower in a catchment have sufficient base flow to maintain this flushing, while dams higher in a catchment have lower base flow and thus should be built in stages.[59] Viducich did not find a correlation between dam height and median particle size, but did conclude that models of sedimentation were highly sensitive to dam height.[60] While de Trincheria et al argue that, in the absence of an ability to exactly predict sediment accumulation, dams should be built in stages "to be on the safe side" (the precautionary principle), raising a dam in stages does require significant costs in finances and effort[61]. At any rate, at least one study concluded that over half of the dams studied that were built in a single stage accomplished community goals for water supply.[62] Viducich concludes that decisions performance is highly site specific – that more dams should be built in stages but that it is not necessary for all sites.

Water Quality

Although users are aware that water quality is best maintained when livestock access is limited[63], a survey of self-help groups found that only 2 out of 16 believed contamination was an issue of concern[64], and Borst and de Haas reported that most users in their study believe the movement of water through the sand sufficiently cleans water.[65] Very little data is available on water quality to assess whether this assumption is accurate. A study by Avis[66] is perhaps the only one which addresses this question. In that study, 24 or 29 dams where a test hole was dug showed not contamination by thermotolerant bacteria (indicators of fecal bacteria), and the 5 with TTCs were judged minimal health risk.

Unlike other aspects of sand dam functions which can easily be assessed by users ("the dam is broken", "there is no water left"), water quality issues are often invisible, and the linkages between water quality problems and their effects are often less obvious. In other words, the lowered psychological impact may not match the importance of its physiological impact. Non-health impacts of water quality are also important, for instance, some villagers have lowered consumption of beans because salty water makes them harder to cook[67]. It has generally been assumed that filtration through the sand provides natural cleansing of the water, and that efforts by users to separate uses (e.g. drinking water taken from upstream, livestock watered downstream), are sufficient to provide clean water. Sand filtration is a known purification technique for microbes, but its effectiveness is dependent on the conditions (e.g. speed of filtration, the presence of native microbe populations), and there is no information on whether these conditions are met in sand dams. Efforts to separate uses are also unclear, there is clear evidence that the separation of uses is not always followed (e.g. animal manure found throughout the sand area above dams). Water quality parameters of most obvious concern are microbes, general salt content, turbidity, and excess nutrients (causing eutrophication). Visible evidence, anecdotal accounts, and preliminary measurements point to these as areas of concern.[68] Other potential problems that are less immediately visible, but can be of equal concern, include pesticide contamination and the presence of toxic metals from geologic sources. A review of SASOL pointed especially to the potential of pesticide and fertilizer contamination.[69] There are reports of high fluoride levels and associated fluorosis in other parts of Kenya (associated with volcanic

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[59] ibid
[60] Viducich 2015
[61] ibid
[62] ibid
[63] Cruickshank 2010
[64] Woodring 2014
[65] Borst and de Haas 2006
[66] Avis 2015
[67] UDO pers comm
[68] Rempel et al 2005, Borst and de Haas 2006, Gijbertsen 2007, Teel "Storage capacity…"
[69] Rempel et al 2005

activity).[70] This review suggested establishing water testing facilities to monitor various parameters. Preliminary evidence suggests pH is not an issue.[71]

Costs and Benefits

Organizations and donors are concerned with the question of whether sand dams are worth (however judged) the investment. By far the majority of documents conclude that there are major benefits to the implementation of sand dams. Direct benefits include use of water for drinking, household uses, and (the largest quantity) for agricultural purposes.[72] Indirect benefits can include a host of economic, health, and other quality-of-life indicators[73]. Often these benefits are reported anecdotally. Sand dams lend themselves to observers rapidly reaching positive conclusions – the dams and neighboring areas have a visual impact which can be easily interpreted as being beneficial. The popularity of sand dams within communities themselves is argued as evidence for their effectiveness - many (or most) communities build multiple dams, and this incentive to build additional dams does not make sense if the first dam were non-functional.[74] Without discounting the importance of these observations, it is helpful to have more rigorous assessments as well, and data from a number of studies have helped to quantify these costs and benefits.

Water proximity is an obvious immediate benefit from sand dams, for instance an assessment in Kitui noted an average of 1.5 to 2.4 hours per day saved by reduced time spent collecting water.[75] A survey of users of dams by UDO self-reported 2-4 hours saved per day[76]. These savings are mostly to women (and children) who typically collect water. Men also reported saving time, as they had decrease distance for herding livestock. Decreased distance to a water source does not necessarily lead to decreased time collecting water, though; in the study by Pauw[77], distance to a water source decreased from 3 to 1 km, but increased water usage meant more collecting trips, and so overall time spent collecting water did not change. Several studies look at the time period over which this water is available. Hoogmoed's model has the river drying within 1.5 months of the dry season starting, whereas in the presence of a sand dam, water lasts throughout the season[78]. Jansen's model shows water availability extended by 140 days in the presence of sand dams[79]. These models are consistent with other observations and anecdotes that water from sand dams can last throughout the dry seasons.

Increased use of water is clearly reported for communities with functional sand dams[80], and is generally considered a positive impact. However, there is concern that there is a lowered appreciation of water as a scarce resource[81], in essence a version of the well-known "Jevons paradox". Thus, increased ease of water availability could have the unintended consequence of lowered efficiency of water use: "There is no sense of channeling water to agricultural activities with the highest rate of return per litre of water utilized. …community action does

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[70] Zolnikov 2014

[71] Teel "Storage capacity…"

[72] Rempel et al 2005, Woodring 2014, Mutiso 2013

[73] e.g. IGRAC Sand Dam briefing note, Rempel et al 2005, Pauw et al 2008, Mutiso 2013

[74] Maddrell 2014

[75] Rempel et al 2005

[76] Woodring 2014

[77] Pauw et al 2008

[78] Hoogmoed 2007

[79] Jansen 2007

[80] e.g. Pauw et al 2006 saw a 345% increase in water usage at dam sites

[81] Rempel et al 2005

not recognize a need to conserve scarce water supplies, especially in time of drought, to assure water will be available for human consumption and other essential uses of water."[82]

Where there is a decrease in total time collecting water, users can then invest this time in other activities, most often it is reported that there is an increase in agricultural activities.[83] For children, it could result in increased attendance in school.[84] Increases in agricultural production are reported for a variety of products from fruits and vegetables to livestock (for instance, there was a reported 25% increase in maize production), with a resultant self-report of increased food security.[85] Self-help groups with UDO report on average 2.7 months extra food security due to the effects of the sand dams.[86] At SASEL, 80% of respondents reported increased food security all or part (not during drought) of the time.[87] [De Bruijn & Rhebergen, 2006] reported positive economic and social impacts in a small study. A UDO review found increased vegetable consumption of 46%, with resulting increased health.[88] Lasage et al also reported improved health indicators[89], while the recent UDO review indicated relatively few people reporting improved health or hygiene as a major benefit.[90]

In one of the better controlled and more extensive studies, Pauw et al found positive effects on a variety the indicators. For instance, families with sand dams had an increase in income (30,000 Ksh) with the crop diversification, whereas those families without sand dams saw an even larger decrease in income across the measured period.[91] This is consistent with another study that found a 9000 Ksh increase in annual income.[92]

While most studies report clear benefits of sand dams, there is evidence that not all livelihood measures change as expected. For instance, Pauw et al found no increase in associated agricultural practices such as terracing or mulching[93]. Likewise the effect on terracing was questioned in the review of UDO.[94] Cruikshank's survey reported economic benefits were highly variable—in some communities a high percentage reported some economic benefits, while in other cases a high percentage reported no economic benefits. [95] Data in Ethiopia[96] seemed to suggest little impact on time spent with domestic or livestock activities.

Benefits as measured in these various ways (e.g. time spent collecting water, agricultural diversity and productivity, income generation) should be weighed against actual and potential costs. Typically such a cost/benefit analysis focuses on financial cost of the dam (and by extension, the opportunity costs of not using these funds for other activities). de Trincheria et al offer one of the more explicit cost assessments of sand dams.[97] They calculate water costing 5.6 euro/m^3 and higher, which would make those sand dams one of the less cost-effective technologies. This high value is largely driven by what they categorize as ineffective dams – dams which have silted, or have structural damage. On the other hand, Lasage et al reported an initial investment of

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[82] ibid
[83] Rempel et al 2005, Woodring 2014
[84] Rempel et al 2005
[85] ibid
[86] Woodring 2014
[87] Rempel et al 2005
[88] Woodring 2014
[89] Lasage et al 2008
[90] Woodring 2014
[91] Pauw et al 2008
[92] Lasage et al 2008
[93] Pauw et al 2008
[94] Woodring 2014
[95] Cruickshank 2010
[96] Lasage et al 2015
[97] de Trincheria et al 2015

$35 per capita in Kitui, which across the dam lifespan would represent a much lower cost than de Trincheria et al's values[98]. Likewise, in Ethiopia the cost over the lifespan of a dam was estimated at $0.40 per m^3 [99] , which is similar to the general value reported in a lifecycle cost review of rainwater harvesting technologies[100], and by Excellent Development, and the lowest lifetime cost across a range of water technologies[101]. The reasons for these clear discrepancies in the calculations need to be resolved.

Aside from strictly financial costs, other concerns have been raised about sand dams. For instance, there has been concern about of sand dams having potential impacts downstream resulting from lowered flows. In other words, if a large fraction of flow is captured in sand dams, there could be negative impacts to communities and ecosystems downstream. Borst and de Haas's estimate that dams capture only 2% of flow[102] is a widely quoted figure supporting the conclusion that sand dams in fact do not capture enough water to greatly impact downstream areas. Aerts et al found a similar value of 2-4% for rainy season[103], and Lasage et al reported 3%.[104] Thus, current estimates point toward little impact downstream, although predictions under future climate change scenarios present a potentially different conclusion (see below).

There are several key issues with interpreting reported data on costs and benefits of sand dams. These studies have understandably focused on self-reporting (e.g. via surveys), which have a greater potential for yielding biased results. For instance, if users see some benefit from sand dams and wish to have additional dams built, they might over-report benefits in the hope that this will encourage organizations in prioritizing their requests. Within studies themselves, bias against reporting negative results is a known and common problem in scientific literature. As is the case in other disciplines (e.g. pharmaceutical studies), it would not be surprising if the overall conclusions of published results are not entirely representative of the true balance of costs and benefits.

Finally, benefits and costs are obviously dependent on social factors in the communities which utilize the dams. For instance, several note the challenge of deciding who gets to use the water, and the potential or actual conflict arising from this challenge.[105] Intrafamily conflict may, however, decrease, and be associated with changing gender roles.[106] Cruickshank's study is the most comprehensive assessment of social factors in sand dam success.[107] There are other good studies on the sustainability of water supply projects demonstrating (for instance) the importance of the depth (vs breadth) of community involvement in a project, and the importance of community involvement in management (but not technical) decisions.[108]

How to valuate less tangible benefits (or costs) is more challenging, but just as important as more tangible aspects of sand dams. This applies not only to social aspects (e.g. effects on community cohesion or conflict), but also to environmental aspects. Studies have rightly focused on the benefits and costs to people and their communities in a more direct sense—for instance, how does this improve their well-being through increased food security? Benefits and costs could also be considered in a less direct manner. For instance, it seems likely that sand dams provide major benefits in maintaining and promoting local ecological biodiversity. In essence, sand dams may be

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[98] Lasage et al 2008

[99] Lasage et al 2015

[100] Batchelor et al 2011

[101] Maddrell "The potential of sand dams…"

[102] Borst and de Haas 2006

[103] Aerts et al 2007

[104] Lasage et al 2008

[105] Rempel et al 2005, Pauw et al 2008, Cruickshank 2010

[106] Woodring 2014

[107] Cruikshank 2010

[108] Marks et al 2014

an effective means of riparian restoration (much as they appear to reestablish natural springs in some areas[109]). Alternatively, under climate-change scenarios where dams are capturing large proportions of the runoff, they could negatively impact downstream ecologies (e.g. the ecosystem within Tsavo East). More attention to these "non-human" benefits and costs would be helpful, not the least because they provide indirect benefits to humans. A good example of this is the anecdotal accounts of increased honey production by bees near sand dams--as the ecosystem changes due to more extended flowering in plants, humans benefit by the increased availability of honey. Techniques for including both quantitative and qualitative data in decision-making are established and used in the field of rainwater harvesting.[110]

Climate Change

More recently, sand dams have been framed in terms of resilience, particularly in the face of imminent climate change.[111] The hope is that sand dams would provide a means for communities to "weather" the changes associated with climate change (no pun intended...). Climate change is generally considered to be a challenge for water supply in the region. Although actual rainfall rates may increase in the near-term, temperature increases (raising evaporation) and long-term decreases in rainfall (not to mention usage increases due to population increases and/or changes in water usage patterns) should result in greater challenges to providing sufficient water to the region.[112] Of specific concern is that sand dams may capture a high proportion of water in a catchment, negatively impacting downstream regions. Models of Lasage and Andele estimate that up to ~80% of water in regions of southern Ethiopia could be harvested by sand dams in the future[113]. Aerts et al likewise estimated that 20-60% of flow would be harvested under a scenario of climate change and increased sand dam numbers.[114] Obviously such large amounts of water captured would deplete downstream water supplies, impacting communities and ecosystems. For instance, Aerts et al predicated an increase in the frequency of years with extreme water scarcity due to climate change.

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[109] Teel "Water Scarcity…"

[110] see UNEP 2014 for a good introduction and review

[111] Pauw et al 2008, Lasage et al 2015

[112] Lasage and Andela 2011

[113] ibid

[114] Aerts et al 2007

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