An appraisal of the effectiveness and sustainability of sand dams to improve water security and resilience in Somaliland

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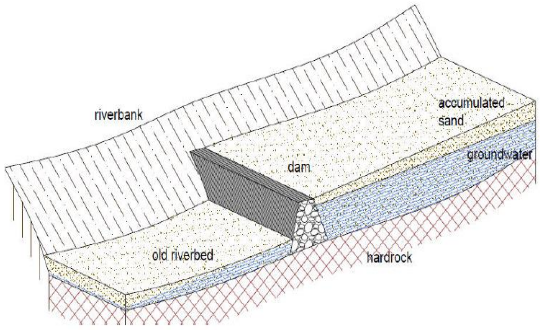
> ***“Storage in sediment significantly reduces evaporation-loss while filtration through sand reduces the risk of bacteriological contamination”***

Sand storage upstream of two sub-surface dams and one sand dam in Huluuq, Somaliland. ©*Lopez-Rey.*

Background

Sand dams and sub-surface dams are increasingly recognised as low-cost and robust rainwater harvesting technologies to enhance water availability in drylands and build resilience to the effects of climate change (Maddrell, 2018; GWP/UNICEF, 2017; WWAP/UN-Water, 2018).

A sand dam is a reinforced concrete or rubble stone masonry structure built across the riverbed of a seasonal river to increase the accumulation of coarse sand upstream and enlarge the natural storage capacity of the riverbed aquifer (Maddrell, 2018). Sub-surface dams are built below the surface of sandy riverbeds to block the downstream groundwater flow and raise the water level in the alluvial aquifer.



Schematic cross section of a typical sand storage dam
(Borst & de Haas, 2006)

Riverbed infiltration techniques have traditionally been used in sub-Saharan Africa and South Asia for decennia to capture and store run-off in sediment and create 'artificial' sand aquifers (GWP/UNICEF, 2017, p.30). Sand dams have been utilised in India for centuries, and were later developed in the beds of African seasonal rivers in Ethiopia, Burkina Faso, Kenya and Zimbabwe (Nissen-Petersen, 2006, p.45). These have been mainly isolated initiatives built by local NGOs or farmer groups to enhance their water supply (RAIN, n.y., p.2). WWAP/UN-Water (2018, p.39) quotes Lasage et al. (2008) and Love et al. (2011) who find that despite the high storage potential of the seasonal sandy riverbeds in arid and semi-arid lands sand dams are currently under-utilised in many regions of Africa. Indeed, figures from Grey and Sadoff (2006), quoted by Foster and Briceno-Garmendia (2010, pp.279-280), show average storage capacity in Africa is estimated at 200 m^3 per capita, much less than other regions such as North America with 5,961m^3 per capita.

Many authors provide evidence of the benefits and positive impacts of sand dams in rural arid and semi-arid areas of Kenya and Ethiopia. There is consensus among researchers (Chritchley and Di Prima, 2012; Neal and Maddrell, 2013; Tuinhof et al., 2012) that sand dams have a comparative advantage over open water storage infrastructure in rural semi-arid and arid lands. Storage in sediment significantly reduces evaporation-loss while filtration through sand reduces the risk of bacteriological contamination. Extensive research on Kenyan sand dams by Lasage et al. (2008), Pauw et al. (2008) Rempel et al. (2005) and De Bruijn and Rhebergen (2006) provided evidence of the positive impact of sand dams in improving social and economic standards, thereby reducing vulnerability and enhancing capacity of communities to cope with drought and climate variability.

Ryan and Elsner (2016) used hydrological modelling and satellite imagery to compare normalised difference vegetation index at sand dam sites and control sites in Makui District (Kenya), identifying higher levels of robustness to periods of extended droughts of ecosystems around sand dams.

The main challenges identified by the different authors include site-selection, design, construction and maintenance as well as the sustainable and equitable management of the source while mitigating potential negative impacts on downstream users.

Aerts et al. (2007) conducted pioneering research studying the robustness of sand dams to climate change using a water balance model-STREAM to simulate water availability in the Kitui District over a period of 100 years. Lasage and Andela (2011) later conducted a comparable study to that of Aerts et al. (2007), applying STREAM model to simulate changes in river discharge under different climate change scenarios in the Dawa river basin in Ethiopia. Their conclusions align with those of Aerts et al. (2007), showing that under future climate scenarios, declining river discharges will cause sand dams to consume a relatively larger part of the discharge, thus affecting downstream users. Lasage and Andela (2011, p.6) estimate the limit to the development of sand dams in 1,000 dams in the Melka Guba catchment and 600 dams in the Mormora catchment, to maintain flow reduction within an acceptable 3% by 2050. Aerts et al. (2007), Lasage and Andela (2011) and Lasage et al. (2015) agree that, from an hydrological point of view, sand dams are a feasible adaptation strategy to deal with current scarce water resources and to improve water security under climate change. The conclusions from these authors converge in the recognition that upscaling sand dam development requires basin-level coordination and development strategies.

Considering this body of evidence, sand dams could be considered a panacea in drylands highly vulnerable to climate change like Somalia, where only 28% of the rural population has access to water supply (UNICEF-WHO, 2019) and the prevalence of water-related diseases such as acute watery diarrhoea is high. Studies conducted by Mohamoud (1990), Oduor and Gadain (2007) and Altai Consulting (2015) conclude that the Somaliland region has favourable climatic and hydrogeological conditions for sand dams. Mohamoud (1990) analysed rainfall, run-off, evaporation, soil infiltration and topography data sets in Somaliland and suggested that, in most non-flat areas, dams can be built to a height of up to 6m to trap medium-sized sand grains without slowing the flood. SWALIM's Potential of Rainwater Harvesting in Somalia report (Oduor and Gadain, 2007) also concluded that ephemeral streams can yield adequate amounts of sand to conserve water for domestic, livestock and irrigation purposes. The WALP project (2015-2018) in Somaliland developed a Wadi Evaluation Tool (WET) allowing for fast and broad spatial analysis of *wadi* water harvesting potential in a selected area, thus allowing the rapid identification of areas where sand or sub-surface dams might be a viable solution to water harvesting (Hydronova, 2019).

Concave-shaped RCC sand dam with riprap built in 2018. Dinqaal community, Woqooyi Galbeed (Picture: Lopez-Rey, 2019)

In the last twenty years, several agencies have piloted sand dams and sub-surface dams in Somaliland as part of resilience and development programmes in coordination with Ministry of Water Resources and Ministry of Environment and Rural Development. With only an estimated 20-25 sand dams in existence in Somaliland, this rainwater harvesting technology remains underdeveloped and still relatively unknown (Amier, 2013; Altai, 2015). Through the appraisal of diverse sand dam experiences in Somaliland, this research project aims to expand the available body of evidence in this geographical context (Altai consulting, 2015; Mohamoud, 1990) and inform the design of new sand dam pilots.

Research objectives

This research project aims to determine whether sand dams are an effective and sustainable solution to improve water security and build resilience in rural communities in Somaliland. Its objectives are formulated as four research questions:

1. What key lessons can be learned from sand dam practitioner experiences in the region?
2. Are sand dams an effective solution for domestic water supply in rural areas of Somaliland?
3. Can sand dams contribute to improving water security and resilience in the context of Somaliland?
4. What factors influence the sustainability of sand dam technology in the context of Somaliland?

Methodology

The first research question is addressed through the desk review of six project documents and case studies capturing sand dam experiences in Ethiopia, Kenya and Somaliland, as well as recognised manuals on sand dam technology: Nissen-Petersen (2000) and Maddrell (2018). Additionally key informant interviews were conducted with three engineers experienced in the construction of sand dams in Somaliland. The lessons learned are captured in a learning framework which later facilitates the appraisal of the studied sand dam sites (Annex 1).

Effectiveness, sustainability and impact on water security and resilience are appraised through a field study of a heterogeneous sample of five rural communities with access to sand dams and sub-surface dams in the regions of Awdal and Woqooyi Galbeed in Somaliland.

In each site, quantitative and qualitative data was collected through sand dam measurements, water sampling, sand sampling, transect walks with GPS data collection and direct observation. Semi-structured group interviews and community mapping were conducted with two distinct group profiles in each community:

- Group A: gender-mixed group including members from the Village committee and the Water management committee (where these exist), as well as pastoralists and riverine landowners upstream and downstream of the dam.

- Group B: composed exclusively of women, including women-headed households living in the village or in areas upstream and downstream of the dam (including pastoralist, agro-pastoralist or riverine farming livelihoods).

In total 95 individuals (57 women and 38 men) participated in the group interviews held from 25th September to 1st October 2019.

Group B community mapping and semi-structured interview in Carracad community, Borama (Picture: Lopez-Rey, 2019)

In addition to the analysis of qualitative data from the semi-structured group interviews, the following quantitative data was generated to inform the research questions:

1. **Water demand coverage**.

During the dry season the recharge of the sand aquifer is considered nil, assuming any inflow from base flow is offset by outflows from evaporation and seepage. Considering the sand aquifer is fully replenished at the end of a normal rainy season, the study estimates the maximum extractable water volume using Nissen-Petersen (2000) formula and compares this volume with the domestic and livestock water demand during the 5-month dry season. The dry season demand is estimated based on the average number of 20L jerry can consumption per household (minimum of 20l/p/d) and the estimated number of small and large livestock heads watering in the sand dam wells reported in the semi-structured interviews.

$$Q = (L \times D \times T) / 3$$

Where:
Q= capacity in cubic meters
L= maximum width of riverbed
D= maximum depth of sand
T=Throwback of the sand reservoir in meters

Volume of extractable water from the sand reservoir = Dam Capacity (Q) x Drainable Porosity

Drainable Porosity (%) = Volume of water that freely drains ÷ Total volume

The present study did not aim to calculate the total water availability over the design life period. This would have required the collection of detailed data on rainfall in the catchment area, specific yield of sediments, evaporation and seepage losses, as well as the estimation of the base flow from the sediments and the riverbanks base flow (Borst & de Haas, 2006; Hoogmoed, 2007 and Hussey, 2003).

2. **Water quality**

Water samples were analysed for turbidity, TDS, pH and thermotolerant coliforms (TTC). The results can be considered only as indicative because the number of sample sites was limited to three and the samples could only be collected once, thus limiting the reliability of the data.

3. **Capital cost, operation and maintenance costs of dam and water supply facilities over a 30-year design life**

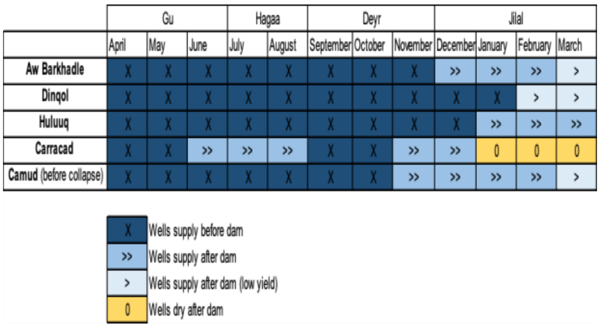
The costs of the dam construction and associated facilities were provided by project implementers for three of the studied. Where the information was not available costs were estimated based on sand dam bill of quantities examples available the key informant interviewees. Despite these limitations on the accuracy of the results, the consistency in the application of assumptions is considered to provide a reliable estimation for the purpose of appraising total lifespan costs for the different dams and types of facilities.

Main findings

Effective solution for improving domestic water supply in rural areas of Somaliland

The field research concludes that **sand dams are a socially acceptable technology with potential capacity to fully cover community domestic water demand during the 5-month dry season**. In all four locations with functional sand dams, the maximum extractable volume of water at the beginning of the dry season is theoretically sufficient to cover 100% of the minimum domestic water needs (20 l/p/d) during the 5-month dry season (150 days). However proper management and monitoring of sand dams is crucial to prevent over-abstraction for other uses. Failure to do so can result in insufficient water availability for domestic use in the dry season.

Overall, the results show that **sand dam construction resulted in net gains of 2 to 5 months of local water availability in the dry season (*Jilal*)** as a direct result of the increased water storage capacity of the alluvial sand aquifer. It is worth noting that the interviewees' responses consider normal rainfall years and not drought years.



	Gu			Hagaa		Deyr			Jilal			
	April	May	June	July	August	September	October	November	December	January	February	March
Aw Barkhadle	X	X	X	X	X	X	X	X	››	››	››	›
Dinqol	X	X	X	X	X	X	X	X	X	X	›	›
Huluuq	X	X	X	X	X	X	X	X	X	››	››	››
Carracad	X	X	››	››	››	X	X	››	››	0	0	0
Camud (before collapse)	X	X	X	X	X	X	X	››	››	››	››	›

X Wells supply before dam
›› Wells supply after dam
› Wells supply after dam (low yield)
0 Wells dry after dam

Figure 1. Seasonal water availability in riverbed wells before and after dam construction. Source: Lopez-Rey (2019)

"The sand dam helped us have water for longer times than before". Camud female participant.

"Drought times were longer and we had to collect water from Nadhi spring during 8 months of the year but after the dam it is only 3 months". Carracad female participant.

Water from covered wells in sand dams is perceived by users to be suitable for drinking without any treatment. All the samples analysed showed relative low levels of mineralization with TDS below 1,000 mg/L. Total dissolved solids can affect water acceptability but is not considered a health concern in WHO drinking water guidelines. pH values in all samples are within the WHO (2017) range 6.5-8.5. Turbidity is also below the 5 NTU maximum WHO standard in all samples except one well which was not adequately covered. TTC was positive in two of the three samples analysed, likely due to poor maintenance and protection of the well and storage tank. While sand filtration can achieve WHO drinking water standards of turbidity, pH and TTC if the source is adequately protected, unprotected or poorly maintained water supply facilities can compromise water quality.

The initial capital cost of reinforced concrete (RCC) sand dams varies between 32,120USD and 67,397USD, with riverbed width as the main variable influencing the total cost. The cost per cubic meter of dam ranges from 312 to 470USD/ m3 for RCC, with smaller dams having higher cost per cubic meter. For the rubble stone sand dam and SSD in Huluuq, the estimate cost was only 69USD/m3.

The average capital cost of the sand dam is 31 USD per capita, for a minimum 30-year design life, thus 1 USD per person with access to water supply per year. In addition to the sand dam cost, the capital investment of a protected masonry well with manual lifting is estimated ar 0.4 USD per person per year, whilst the capital cost of a masonry well with solar pumping unit, storage and distribution system requires an average investment of 0.8 USD per person per year.

Protected masonry well with solar pumping system in Huluuq sand reservoir. Source: Lopez-Rey (2019)

In-kind community contribution with materials and labour was identified at two sites of the five studied only. At all sites, the construction costs of the dam and wells were almost fully subsidised by external agencies with no capital investment cost-recovery.

Water is accessed free of charge at all communal facilities and therefore affordability is not a limitation for users. The cost of adequate dam and gabions maintenance over a 30-year project life ranges between 0.7 and 1.2USD per person per year. The operation and maintenance costs of water supply facilities varies from 0.1 to 3 USD per person per year depending on the level of technology selected.

Contribution to water security and resilience

Household resilience

A positive impact of sand dams cited by interviewees across all sites is the improvement in water availability during the dry season, with a net gain of 2 to 5 months of local water supply, as shown in Figure 1. This translates to improved self-reliance and many direct benefits for communities. Firstly, reduced time to fetch water, as illustrated in the example of Carracad. Secondly, lower expenditure on water during the dry season, as mentioned by Diinqal community. Thirdly, an increase in the amount of water used by households (slight to large increase reported by all communities). Fourthly, extended availability of water for livestock resulting in improved animal health and body condition (reported by all communities). Indirect benefits of the above include; more time available to women for childcare and income generation, increased household savings and better hygiene practices.

> ***"We have more water in the house now because the sand dam increases water".*** *Huluuq woman participant.*

Livelihoods resilience

The results show a general improvement in the yield of irrigation wells located upstream of the dam, except in Diinqal, where the interviewees do not appreciate any change. However, this dam is just over 1-year old and it may take several years for the sand dam to reach its full storage capacity. Improved yield results in improved productivity and income for upstream farmers. The results also evidence that farmers located downstream can be negatively affected by a reduction in wells yield and alluvial sediment. This negative impact is evidenced by the dissatisfaction of downstream famers in two communities. In the other three, there is either no presence of farmers 1km downstream, or farmers downstream benefit from a second dam. These results confirm the learning framework recommendation 2.6, regarding the need to avoid siting of dams where irrigated farming exists within 1-2 km downstream. Alternatively, several sand dams in series can be proposed, as in the case of Huluuq and Camud.

The results also show a positive impact on livestock husbandry activities. All five communities reported good livestock body condition during normal dry seasons, which is partially attributed to increased water availability. Figure 2 shows that in Huluuq the maximum extractable volume of the three dams in series is 187% of the domestic and livestock demand in the dry season (including estimated demand from nomadic pastoralists). Thanks to this surplus, Huluuq farmers are able to irrigate large surfaces of fruit trees and vegetable crops even during the dry season. In the other three sites, the coverage of domestic and livestock demand during the dry season varies from 58% to 77%, hence alternative water sources are still required. These results are likely to be underestimated, as only water stored in the sand reservoir is considered and not the groundwater in the permeable bedrock.

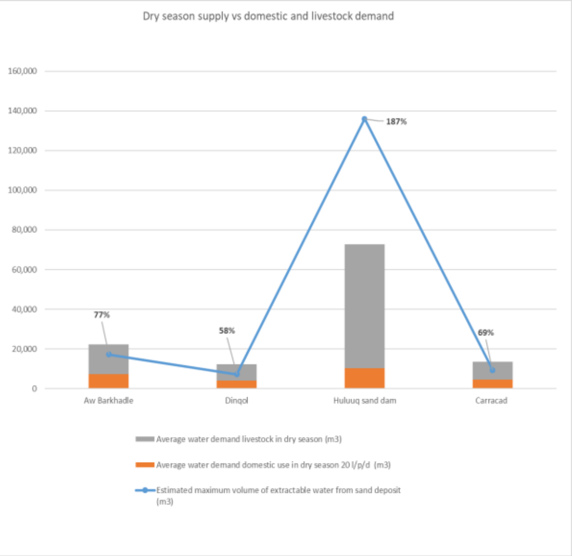


Figure 2. Dry season sand dam supply vs domestic and livestock demand. Source: Lopez-Rey (2019)

Livelihood diversification was observed in two communities where farmers with access to the riverbed wells had introduced home gardens and cash crops such as guava and citrus. Other new sources of income include petty trade with nomadic pastoralists, sale of sand for construction and sale of water to private vendors. This represents a source of additional income for a handful of households but it can also lead to accelerated depletion of the community resource in the absence of regulation.

"Even in 2017 drought the wells had water, it was low but they never dried".
Huluuq woman participant.

Ecosystems resilience

Three communities reported a visible increase in natural riverine vegetation and biodiversity upstream, likely to be attributed to an increase in the water table. No negative impacts on the downstream natural riverine vegetation were observed at the studied sites or cited by the interviewees.

Further research on the potential of sand dams for ecosystem-based adaptation is highly relevant in the climate change vulnerable context of Somaliland. As concluded by Ryan and Elsner (2016) increased biomass enhances ecosystems' resilience to climate variability and increases drylands´ adaptive capacity.

The above benefits have direct causal links to improved food security as well as nutrition and health, which in turn contribute towards enhancing household and community resilience capacities to cope with climate-related shocks.

Open well on the sand reservoir used for orchard irrigation. In Huluuq community. Wooqoyi Galbeed. Picture: Lopez-Rey (2019)

Factors influencing sustainability

The analysis of factors influencing the sustainability of sand dam technology in the rural context of Somaliland indicates very **high potential for long-term sustainability** but also evidences current shortcomings in sand dam sustainability projects. In some cases, insufficient knowledge of this relatively new technology in Somaliland hinders communities' ability to participate in the site-selection and design phase in a more informed and proactive manner. Adequate sensitisation through visits to other sand dams and broader community consultation on site-selection can mitigate potential negative impacts on downstream dwellers, such as reduced well yield and increased erosion of unconsolidated riverbanks. Ensuring there is no farmland within at least 1km downstream of the dam and gabion walls on unconsolidated riverbanks are identified as key measures to mitigate potential negative impacts downstream.

"Upstream households have much more water now but the ones downstream have less water and less sand". *Aw Barkhadle female participant.*

The findings also illustrate the importance of considering pre-existing conditions, community user preferences and willingness to pay when designing sand dam water abstraction facilities. To be effective and accepted by communities, sand dams need to improve upon pre-existing facilities either by reducing time/distance for water collection or by reducing water expenditure, or both.

Adequate sand dam **maintenance over a 30-year lifespan ranges from 0.7 to 1.2 USD per person per year**. Maintenance costs of associated water supply facilities range from only 0.1 USD/person/year for manual lifting from wells, up to an average of 3 USD/person/year for solar piped-water systems. The results suggest affordability is not a limiting factor of sand dam maintenance, nor is the availability of technical services, materials and spare parts.

The key limiting factors identified are:

1. Low sense of community ownership and buy-in; insufficient knowledge of sand dam technology sometimes results in limited community participation in the design process.
2. Insufficient community awareness and capacity to conduct essential sand dam maintenance such as the repair of gabions to protect the dam from erosion and potential collapse.
3. Low user satisfaction levels and unwillingness to pay for repairs and maintenance where convenience and accessibility is not visibly improved by the new sand dam and facilities.

“When it was first build the community was not aware how important the dam was” Carracad male participant.

View of partially washed-away gabions in Carracad dam, Borama.
Picture: Lopez-Rey (2019)

Conclusion and recommendations

The findings of this research are based on a limited sample of sites therefore the results are not statistically representative and cannot be extrapolated to all sand dams in Somaliland. The research however meets its objective of appraising the effectiveness, sustainability and impact of sand dams in Somaliland, directly expanding the limited body of evidence on this topic and in this geographical area by complementing the case study of four sand dams conducted previously by Altai (2015).

This study strongly recommends the piloting of sand dams in new locations of Somaliland based on the analysis of effectiveness, sustainability and positive impacts of sand dams to alleviate water insecurity and shore up community resilience to climate change. Available local technical capacity, a supportive public policy framework, the relative security and stability of Somaliland as well as the favourable climatic and hydrogeological conditions confirmed by Mohamoud (1990), Oduor and Gadain (2007) and Altai (2015) all contribute to a highly conducive environment to realize the potential of sand dams in communities with seasonal rivers.

This study recommends building on the lessons learned from engineers, implementing agencies and line ministries in Somaliland and other experiences in the region, some of which are captured in the learning framework (Annex I). In particular, the design of sand dam projects should consider the coverage of domestic and livestock water demand for host and nomadic populations in the dry season (as well as other uses like water trucking). Sand dams built in series can be a suitable option to further enhance storage capacity and meet the projected demand with minimum downstream impact.

To maximise benefits and sustainability, sand dam projects need to be jointly led with communities from the initial decision-making stages of site-selection and design of water supply facilities. This requires investing in building capacity and creating in-depth community awareness around this new technology. To remain effective in the long term, post-implementation support and monitoring is critical to the sustainability of community-managed sand dams and facilities

Finally, this study also recommends accurately documenting future pilot sand dam projects to record lessons learned and challenges faced. Scaling up and refining this experience in the context of Somaliland has the potential to expand this valuable and innovative technology to benefit communities in other Somali regions where climate-resilient water supply solutions such as sand dams remain underdeveloped.

Annex I. Summary of practitioners' best practice and lessons learned

1. Site selection (hydro-geological and topographic factors)

1.1 Lack of emphasis on hydro-geological investigation, soil profiling, infiltration analysis and gradient study prior to implementation can put at risk the long-term sustainability of the infrastructure (KI2, 2019; HYDRONOVA, 2019, p.17).

1.2 Inflow should be sufficient to provide enough sand to fill the dam reservoir and store water in the pores (Maddrell, 2018, p.32; VSF, 2006, p.21). Dense vegetation and local knowledge on tree species can indicate areas with abundant sub-surface water (VSF, 2006, p.19; Nissen-Petersen, 2000, p.8). The presence of waterholes suggests that the riverbed does not leak into the ground below and can be a good indication for siting (Nissen-Petersen, 2006, p.50).

1.3 ALTAI (2015, p.144) KI2 (2019), Maddrell (2018, p.32), SASOL (2004, p.1) and VSF (2006, p.18) recommended topographical gradients between 0.125 and 4%, to ensure adequate flow and reduce silt accumulation. SSD however can be suitable where gradients and velocities are lower (VSF, 2006, p.17).

1.4 Sand dams are recommended for riverbed sections with a maximum width of 25m to reduce the cost of reinforcement while sub-surface dams of natural clay and soil may be more appropriate in wider riverbeds (Nissen-Petersen, 2006, p.49). Well-defined and stable riverbanks of at least 1.5m height decrease the risk of lateral flow and leakages (ALTAI, 2015, p.84; VSF, 2006, pp.18-21). Local knowledge on river morphology and flow during flood episodes should be considered for siting (KI2, 2019) avoiding bends or sections where the watercourse could bypass the dam (Nissen-Petersen, 2006, p.49; VSF, 2006, p.21).

1.5 To minimise costs and maximise water storage, Nissen-Petersen (2006, p.50) recommends to build sand dams and SSD on underground dykes of rock.

1.6 The riverbed should have a solid rock foundation which can support the weight of the dam, and which is not porous (Maddrell, 2018, p.32; VSF, 2006, p.21). Dams built on clay soils may subside (SASOL, 2004, p.11). Dam walls should never be built on fractured rocks or large boulders because such walls cannot be made watertight (Nissen-Petersen, 2006).

1.7 Optimal sites are those with sand and gravel soils with impermeable bedrock at depths of 4-6 metres (Maddrell, 2018, p.45; VSF, 2006, p.18) and permeable river banks to allow base flow recharge the aquifer (KI2, 2019). Thick alluvial deposits such as coarse sand are most optimal (SASOL, 2004, p.22). Low performance of sub-surface dams has been associated with very low infiltration in very fine sands (KI2, 2019; Nissen-Petersen, 2006, p.49).

2. Site selection (socio-economic factors)

2.1 Baseline data on individual and community needs and aspirations should be collected through detailed community assessment to understand water access and utilisation prior to site-selection (IRC, 2014, p.4; SASOL, 2004, p.15). VSF (2006, p.47) identify the inclusion of local livestock keepers in the site selection process as a key success factor in Turkana (Kenya).

2.2 Where the technology is unknown, the community may require sensitization to understand how dams work and take informed-decisions. This can be best done by visiting other sand dams as suggested by KI3 (2019) and KI1 (2019).

2.3 ALTAI (2015, p.145) suggests preliminary assessments to map land ownership and mobilise communities through consultation processes can address power imbalances and ensure infrastructure remains public. Dams should not be constructed on private land and owners of adjacent land should agree to give way to the site (Maddrell, 2018, p.107; VSF, 2006, p.19).

2.4 The site should be easily accessible, preferably in close proximity to dwellings and the main road (SASOL, 2004, p.11; VSF, 2006, p.21). Large distance from local communities is a common cause of disuse of dams (ALTAI, 2015, p.136).

2.5 KI1 (2019) and KI3 (2019) highlight the importance of avoiding sites where there are farmers within 1-2km downstream of the dam because of increased erosion by flash floods and potential reduction in well yields. Further downstream, these effects are negligible.

3. Sand dam design and construction

3.1 Design is sensitive to river morphology, depth to the bedrock, river width, height of the banks, gradient and sediment type. Best practice highlights from interviewed engineers and technical manuals include:

- To avoid silt storing behind the dam, Nissen-Petersen (2006, p.51) and Maddrell (2018, p.130) promote the construction of the dam in stages, with the spillway height raised by 30 cm with each major flooding in order to harvest the heavier coarser sands and allow lighter fine sands and silt to spill over. Other practitioners suggest to start with 1m, then increase the height by 80cm (KI2, 2019).
- Spillway width should be at least the width of the riverbed (KI1, 2019).

- Wing walls should be fully embedded in the river banks, up to 7m for loose soils and about 5m for hard soils (SASOL, 2004, p.43)
- Nissen-Petersen (2006, p.52) states that "*dam walls must be keyed 1 metre into solid and impermeable soil and the thickness of the key should be 0.55 of the height of its dam wall*". When the dam foundation is built on solid bedrock, vertical steel reinforcement bars should be drilled into bedrock (Maddrell, 2018, p.93). Details on trench digging are provided by SASOL (2004, p.45).
- For the dam to support the pressure of sand and water, Nissen-Petersen (2006, p.52) recommends "*the width of the base of the dam to be 0.75 (3/4) of the height of the dam wall. The width of the crest and its height on the downstream side should be 0.2 (1/5) of the height of its dam wall*". Nissen-Petersen (2006, p.52) also suggests the wall on the upstream side should lean in the direction of water flow by a gradient of 0.125 (1/8).
- KI3 (2019) suggests concave dams have greater resistance to the pressure of sand and water.
- The spill-over apron "*should be of the same width as the dam wall and extend up along the wing walls. Large stones should be set into the concrete to break the force of water spilling over*" (Nissen-Petersen, 2006, p.52).

3.2 Detailed guidelines on concrete and stone masonry construction techniques can be found in Maddrell (2018), Nissen-Petersen (2006) and SASOL (2004).

3.3 Construction should take place during the dry season when rain damage to structures is unlikely (IRC, 2014, p.7; VSF, 2006, p.20; HYDRONOVA, 2019, p.90).

3.4 In order to improve work quality and accountability of contractors, HYDRONOVA (2019, p.90) recommends 'prequalification' of companies, and close construction monitoring by a skilled engineer.

4. Water abstraction, operation and maintenance

4.1 To avoid weakening of the structure and maximize water storage KI1 (2019), KI2 (2019), KI3 (2019), Maddrell (2018, p.135) and Nissen-Petersen (2006, p. 53) recommend the following minimum maintenance of dams:

- Replacing the gabions or stone riprap to protect the spillover apron and the base of the wall from erosion.
- Repair erosion damage in the wing walls and the crest caused by big boulders during floods.
- Removing clay top layer every 1 or 2 years to allow good water infiltration.

4.2 The construction and maintenance of the associated water supply infrastructure and requires a high level of technical knowledge (IRC, 2014, p.6). Projects should consider and attempt to quantify maintenance costs, complexity of potential repairs and access to spare parts, paying close attention to water demand and projected use of infrastructure. (ALTAI, 2015, p.92).

4.3 It is important to consider other uses in the design of supply infrastructure (SASOL, 2004, p.9). Separate distribution mechanisms, for example by channelling water from shallow wells to tap stands and livestock troughs, may address contamination issues and improve convenience (HYDRONOVA, 2019, p.86).

4.4 Communal water supply facilities should be placed strategically, acknowledging the groups that may benefit from each (ALTAI, 2015, p.119). The use by non-community members such as nomadic pastoralists and water truckers should be considered in the design of facilities (HYDRONOVA, 2019, p.25).

4.5 Contamination may result from open defecation, animal carcasses and faeces and polluted surface water run-off (Maddrell, 2018, p.72; HYDRONOVA, 2019, p.86). These risks can be mitigated by incorporating sanitation and hygiene promotion and water quality monitoring (HYDRONOVA, 2019, p.83).

4.6 The development of cost-recovery mechanisms is necessary to sustainably finance life-cycle costs if communities are not to receive continued external assistance (ALTAI, 2015, p.88; IRC, 2014, p.6). ALTAI (2015, p.117) and HYDRONOVA (2019, p.94) recommend considering the roles which government, the community and public-private partnerships can play in management and service delivery.

5. Management, capacity building and enabling environment

5.1 The importance of committed local management is recognised as a critical factor for ensuring long-term sustainability and should begin at an early stage, before the site selection process (VSF, 2006, p.47; HYDRONOVA, 2019, p.93).

5.2 Identifying and strengthening existing water management groups can play a key role (HYDRONOVA, 2019, p.93). Supporting existing community-led processes can be more effective to create ownership than externally imposing water committees (ALTAI, 2015, p.85). SAHEL (2006) project evaluation concludes that engaging with Self Help Groups largely contributed to the success of sand dam projects in Kenya and maximized the benefits beyond water supply access.

5.3 The Water Management Committee should be formalised in by-laws defining roles and responsibilities (IRC, 2014, p.4; SASOL, 2004, p.9). All target groups and their aspirations should be included in this process (VSF, 2006, p.19).

5.4 In terms of capacity-building, KI3 (2019), SAHEL (2006, p.30) and HYDRONOVA (2019) recommend exchange visits of community representatives to successful sites, with practical demonstration and community consultations.

5.5 Many practitioners have noted the importance of community sense of ownership and its influence on sustainability (Maddrell, 2018, p.68; SAHEL, 2006, p.31; VSF, 2006, p.48). SAHEL (2006, p.5) note that community groups appreciate an approach which is "*serious, focused and transparent*". Managing budgets transparently and keeping record of all costs and community contributions encourages community commitment to maintain the asset (SASOL, 2004, p.14). K11 (2019) and Maddrell (2018, p.68) highlight that community contribution is essential for sustainability.

6. Risk mitigation

6.1 Interventions which alter communal management dynamics have the potential to reinforce existing power imbalances, disempower specific groups and exacerbate existing conflicts (SAHEL, 2006, p.40). Benefits may not be shared equally and depend largely on land ownership and dam siting, which may render some holdings more accessible for irrigation than others (IRC, 2014, p.6). In order to mitigate conflicts, a participatory assessment of local power dynamics and of the institutions through which grievances are addressed is crucial (SAHEL, 2006, p.40; HYDRONOVA, 2019, p.93). Land tenure issues should be addressed through community dialogue prior to implementation (ALTAI, 2015, p.121; VSF, 2006, p.19).

6.2 Unregulated withdrawals by private water truckers represent a significant threat to the sustainability in areas where water trucking is a growing business (HYDRONOVA, 2019, p.26). Projects must include actions to support communities in controlling appropriation of water, for example by establishing a protected throwback area and by creating regulation to ensure that the Water Management Committee has the right to control non-communal withdrawals (HYDRONOVA, 2019, p.17).

6.3 Quality control and technical backstopping during construction is essential both in mitigating against the failure of dams and in ensuring the safety of labourers. Insufficient knowledge and skill can lead to poor site choice, errors in hydrological calculation and design work and poor execution of construction procedures, which have been noted as the most important reasons for sand dam failure by ALTAI (2015, p.81) and Maddrell (2018, p.131).

6.4 Several practitioners have also noted that the application of short-term 'value for money' measures of success can undermine longer-term project outcomes such as creating strong community ownership and sustainable water management structures (ALTAI, 2015, p.82; SAHEL, 2006, p.40).

6.5 Project design should be informed by an assessment of the potential environmental impacts and necessary mitigation measures, including risk of flooding and erosion (KI2, 2019).

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