The potential for sand dams to increase the adaptive capacity of East African drylands to climate change

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Abstract/Summary
Drylands are home to more than two billion people and are characterised by frequent, severe droughts which are expected to be exacerbated by climate change. A potentially simple and cost-effective mitigation measure against drought are sand dams. This little-known technology promotes subsoil rainwater storage to support dryland agroecosystems. This study analyses multi-year satellite imagery to compare vegetation at sand dam sites and control sites over selected drought periods, using the normalised difference vegetation index. The results show that vegetation biomass was consistently and significantly higher at sand dam sites during periods of extended droughts. It is also shown that vegetation at sand dam sites recovers more quickly from drought. The observed findings corroborate other modelling-based and socio-economic research. Using past periods of drought as an analogue to climate change conditions, this study indicates that sand dams have the potential to increase adaptive capacity and resilience to climate change in drylands.

Introduction

Drylands cover more than 41 % of the world's surface (Safriel and Adeel 2005), and they are home to 2.3 billion people, or nearly 30 % of the world's population (UNDP 2014). Over one billion people from the developing world rely on dryland natural resources for their livelihoods (UNDP 2014).

Drylands are characterised by frequent, severe drought and climate extremes. Climate change is expected to increase the frequency and exacerbate the impacts of these, resulting in increased water scarcity. For most dryland regions, climate models predict higher temperatures, decreased precipitation, and an increase in intensity and frequency of extreme events such as droughts and heavy rainfall (So ¨rensen et al. 2008). Observational data suggests East African drylands are getting warmer with less rainfall, resulting in a drying effect that will increase with further climate change (Funk 2010). This threatens the ecosystems and people who depend on them, particularly agroecosystems where humans are heavily reliant on ecosystem resources for their livelihoods (Boko et al. 2007; Fischlin et al. 2007; Speranza 2012; Kilroy 2015). There is therefore an urgent need for appropriate and sustainable technologies that improve the ability of dryland communities and ecosystems to be resilient in the face of such challenges (Tucker et al. 2015).

In recent years the international community has turned its attention to adaptation responses to climate change (Boko et al. 2007; Schipper and Burton 2009). Sand dams are an example of such a potential response but are currently only promoted by a small number of national and international non-governmental organisations (NGO's). Sand dams are rain water harvesting structures which are already being used as a response to conditions of water scarcity in drylands. They are common to south-east Kenya only, and little systematic research has been done on them. However, the small number of studies that have been carried out suggest positive, sustainable, environmental and social impacts that could increase adaptive capacity to climate change conditions (Lasage et al. 2008; Pauw et al. 2008; Quilis et al. 2009).

It is timely to consider the usefulness of the wider application of sand dams as an appropriate technology for drylands in this policy environment. The first sand dam projects were implemented [50 years ago, with the majority built in the last 15 years, so there is now the opportunity to empirically test the effectiveness of sand dams during drought periods using remote sensing approaches. This paper describes such a research project. We will do this by first introducing the basic principles of the sand dam concept and contextualise its potential to improve climate change-related drought resilience. The methods section will then introduce data sources, the locations of case study dams and analytical approaches. This is then followed by a presentation of the results and a discussion of their significance for climate change adaptation and mitigation.

Principles of the sand dam concept

A sand dam is a reinforced concrete wall built across a seasonal riverbed to harvest rainwater (Fig. 1). Its objective is to support multiple uses, including water for human consumption, small-scale irrigation and livestock watering (Foster and Tuinhof 2004; Hut et al. 2008).

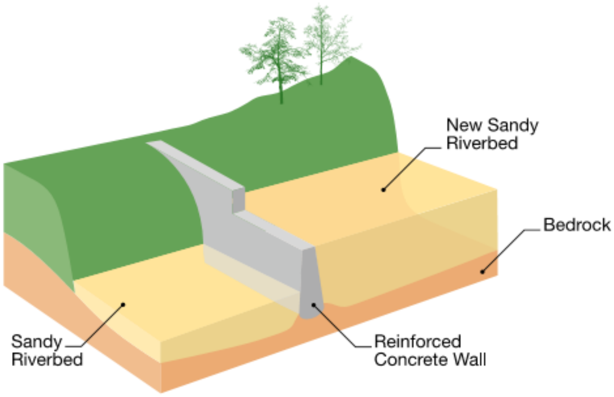


Fig. 1 Placement of a sand dam in a river bed. *Source* Excellent Development (2011)

After construction, the first seasonal rains fill the dam area with water, silt and sand in both upstream and downstream directions. The coarser sand has the highest settling velocity and deposits upstream of the dam. The newly deposited sand provides additional water storage capacity. Suspended material with smaller grain sizes, such as silt, will wash over the top of the dam and continue downstream (Fig. 2).

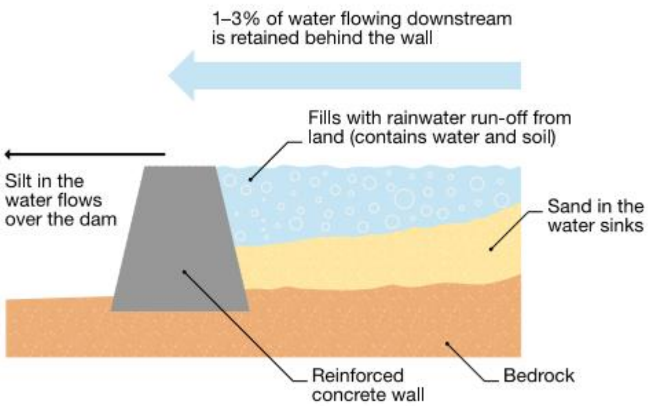


Fig. 2 Conceptual illustration of how a sand dam works. *Source* Excellent Development (2011)

Sand dams are carefully designed so that the natural flow of the river is not altered, so as to avoid erosion downstream of the dam. For example, dams are placed on long straight stretches of river rather than before a bend. A secondary spillway centres the water within the river bed and wing walls are built to keep the flood waters from going around the sand dam, causing erosion and eventually undercutting the dam walls. Good land management practices accompany any sand dam build. Terracing and plantings occur in the catchment area to prevent run off, erosion and siltation. This is important because silt reduces the dams' ability to store water. Small rills or gullies are blocked to prevent soil erosion with plantings, sand bags or smaller sand dams (Maddrell and Neal 2012).

With each rainfall event, the size of the sand reservoir increases allowing more water to be stored. When mature, the dam comprises between 25 and 40 % water (Maddrell and Neal 2012). The dam also obstructs groundwater naturally flowing through the permeable riverbed. This creates higher upstream groundwater levels that subsequently infiltrate into the adjacent riverbanks, thus also raising groundwater levels in those riverbanks (Hoogmoed 2007). The subsurface groundwater flows and seasonal rains recharge the groundwater aquifer (Hoogmoed 2007).

Water can then be extracted by the local population by using wells, pumps or scoop holes in the riverbed or banks upstream of the dam (Quilis et al. 2009). The saturated sand material will also shield water from evaporation and contamination from animals. Additionally, sand acts as a natural slow filter, purifying the water and making it safer for humans to drink (Avis 2014).

The potential for sand dams to increase adaptive capacity to climate change

Adaptive capacity can be understood as the capability of a system to respond to climate variability by reducing vulnerability or enhancing resilience (Adger et al. 2007). These two elements, vulnerability and resilience are further defined: vulnerability as the ability or inability of individuals and systems to respond to external stress placed on livelihoods (Kelly and Adger 2000); resilience as the capacity to absorb such disturbances so as to retain function, structure, identity and feedbacks (Walker et al. 2004).

In general, agro-ecosystems in the drylands of Africa have low adaptive capacity and high inherent exposure to climate change. Subsequently, subsistence farmers and ecosystems currently have low resilience to climate shocks such as droughts (Boko et al. 2007). Their high vulnerability is due to the reliance on rainfall for economic and social development. Makueni District in south-east Kenya is an example of such an agro-ecosystem. Makueni has experienced frequent and severe droughts in recent decades; such conditions are analogous to those projected under climate change (Christensen et al. 2007; Fischlin et al. 2007). Makueni has also experienced increasing population and population density since 1950, when it was barely inhabited. Before 1950, the dominant arid and semiarid areas served as extensive grazing grounds, but these areas are now permanent croplands (Speranza 2010) with an average population density in 2009 of 110 people per square km (Kenya National Bureau of Statistics 2013). The main issues facing the county are population growth (1.4 % per year), high levels of poverty (64.3 %), inadequate water supplies and population pressure on arable land affecting agricultural productivity (Republic of Kenya 2013). It is clear that anthropogenic pressures in the region have increased substantially in past decades, providing an added need for more sustainable water management that increases resilience to drought.

There is substantial concern that the adaptive capacity of the dryland pastoralists, smallholder and subsistence farmers may be overstretched by climate change, leading to increased poverty and unsustainable coping strategies (So ¨rensen et al. 2008). This is reflected by a renewed interest in ambitious schemes such as the Great Green Wall where large-scale tree planting means aims to reduce desertification in the Sahel region (O'Connor and Ford 2014). Smaller-scale technologies such as sand dams are an alternative way to increase resilience and decrease vulnerability of natural and human systems, and to increase their adaptive capacity (Boko et al. 2007; Adger et al. 2007). In south-east Kenya sand dams have proved to be relatively cheap and easy to build. Most of the cost is in construction, and thereafter they require low or no maintenance over their lifetime of 50 years or more. In Kenya the community provides much of the labour voluntarily, but siting expertise and coordination is provided by a handful of local NGO's. Steel and cement are bought in (Ertsen and Hut 2009). The average cost per m3 of water stored is around US$1.15. (Akvopedia 2016). This makes them a cost-effective and accessible adaptation technology for the most vulnerable in society.

Vegetation plays an important role in drylands through valuable provisioning, regulating, supporting and cultural services to humans. Resilience to drought in drylands is key to the continuation of these services under climate change conditions. Hydro-geological models suggest sand dams are a way to increase groundwater due to a c. 40 % increase of storage in riverbanks (Borst and de Haas 2006; Jansen 2007; Hoogmoed 2007). Moreover, modelling suggests the sand reservoir fills within days of the first rains, remaining through the season and river banks then fill within a month of the first rains. Groundwater is maintained throughout dry seasons and drought (Borst and de Haas 2006; Hut et al. 2008; Quilis et al. 2009) increasing the length of time communities have water reserves by up to 2.5 months (Pauw et al. 2008). These features enhance the resilience of vegetation to drought at sand dam sites.

Context, aims and activities undertaken

Previous studies have not empirically demonstrated this enhanced resilience, but land cover change detection studies on the impact of sand dams go some way to validate modelling assumptions. Manzi and Kuria (2011) found that sand dams have a positive relation to land cover type; the presence of sand dams can create a shift in land cover from bare soils, before sand dams were built, to vegetated cover types afterwards. However, the study did not use control sites and the observed increase in vegetation may instead reflect the reported general greening in the region over the period studied (Conway et al. 2008).

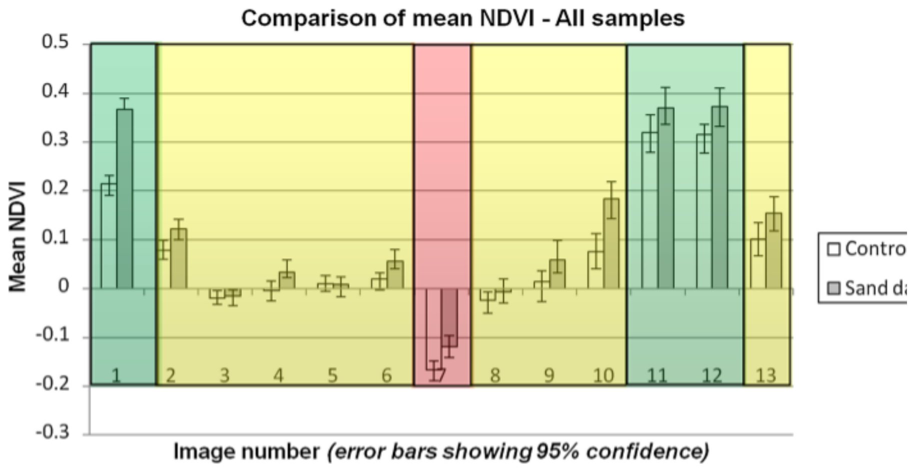
The aim of this research is therefore to empirically test the hypothesis that sand dams increase the adaptive capacity of drylands by increasing the resilience of vegetation through times of water scarcity. This research tests the findings and assumptions from hydro-geological modelling studies (Borst and de Haas 2006; Hut et al. 2008; Quilis et al. 2009). A key indicator for this will be vegetation health, as it can be expected to improve at sand dam sites due to the additional water stored in sand dam reservoirs and riverbanks. Vegetation growth is frequently limited by lack of water, thus the relative density of vegetation is a good indicator of drought (Weier and Herring 2000).

Normalised difference vegetation index (NDVI) is the most commonly used index for vegetation density. Changes in vegetation can therefore be measured by differences in the NVDI calculated from satellite images. Furthermore, indications of the impact of sand dams on vulnerability can be identified from changes in NDVI. Specific objectives for this study include:
1. to measure and compare vegetation at sand dam and control sites over selected periods of drought using NDVI;
2. to draw inferences from results on the impact of sand dams on vegetation in periods of water scarcity;
and 3. to draw inference from results on the potential of sand dams as an adaptation response to climate change in drylands.

Main results and lessons learnt

Throughout the 7-year observation period, NDVI was consistently higher at sand dam sites.

Fig. 4 Comparison of mean NDVI between 2005 and 2012. Periods of extreme drought are indicated by *red shading*, periods of drought by *yellow shading* and periods of relative greening by *green shading*



The results of this research project demonstrate that sand dams substantially increased the ability of drylands to buffer extended periods of water scarcity. NDVI is a proxy for plant health, productivity, and biomass. A relative increase in NDVI at sand dam sites compared to non-sand dam indicates an improved resilience to adverse conditions. Mean NDVI at all sand dam sites was consistently significantly higher than at control sites during periods of water scarcity. Even during 'Drought' and 'Extreme Drought' conditions, NDVI values at sand dam sites were consistently higher than controls.

It was also demonstrated that vegetation at sand dam sites recovered more quickly from drought. After showers occurred within a drought period, a 'Relative Greening' effect was more substantial at sand dam sites.

Conclusions and Recommendations

This study provides the first robust empirical quantification that sand dams have a substantial potential to mitigate drought events and addresses the need for more rigorous evidence base that can inform decision-making in climate change adaption (De Souza et al. 2015). Sand dam sites show consistently, statistically significantly higher mean NDVI throughout the 7-year observation period.

We also observed a buffering effect of sand dams due to a slower drying out of vegetation at sand dam sites at the onset of droughts, and faster, more sustained recovery after precipitation. These findings support the hypothesis that sand dams are an effective approach to increase the adaptive capacity of drylands by increasing the resilience of vegetation through times of water scarcity. Increased resilience increases the adaptive capacity of drylands to climate change. The satellite-based observations of this study agree well with the literature on modelled groundwater flows and storage around sand dams, as well as impacts on land cover and socio-economic indicators. It can therefore be concluded that the relatively simple sand dam technology is highly appropriate as an adaptation response to climate change in drylands. Due to their simple design and construction, sand dams are therefore a useful and cost-effective development approach. They also provide an interesting tool for mitigating the future effects of climate change.

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