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

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Declaration

I certify that the work submitted is my own and that I have duly acknowledged any quotation from the published or unpublished work of other persons.

Signature and date

15/10/2012

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iv. Abstract

Drylands are home to more than two billion people, they are characterised by frequent, severe droughts which are expected to be exacerbated by climate change. Sand dams are a little known technology to harvest rainwater in dryland agro-ecosystems. Using past periods of drought as an analogue to climate change conditions, this study aims to understand the potential of sand dams to increase adaptive capacity to climate change in drylands.

Landsat satellite images were analysed to compare vegetation at sand dam and control sites over selected periods of drought, using the Normalised Difference Vegetation Index. Vegetation biomass was consistently, significantly and substantially higher at sand dam sites. This corroborates past research which identified related impacts on ground water, land cover, and socio-economic indicators.

Sand dams enhance the resilience of vegetation during drought disturbances, and an increase of Net Primary Productivity at sand dam sites is indicated. Both resilience and productivity increase adaptive capacity of drylands.

Future directions should focus on validation through field studies, examination of a longer period of time, and the impact of sand dams on land cover composition. The impact of sand dams on Net Primary Productivity as related to yield and income should also be examined in collaboration with social sciences. Additionally, the potential for sand dams to enhance carbon sequestration is of interest for climate change mitigation.

v. Acknowledgements

Thank you to the communities for building the sand dams and sharing information about them including the Wikwatyo Niweas, Makuta Mwea, Nzyaa Muisyo and Nzyaa Muiyso Self Help Groups.

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1. Introduction

Rationale

Drylands cover more than 41% of the world's surface (Safriel and Adeel, 2005) and they are home to more than 2 billion people, or nearly 40 % of the world's population (Koohafkan and Stewart, 2008). Over one billion people from the developing world rely on dryland natural resources for their livelihoods (UNDP, 2012).

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. This threatens the ecosystems and people that depend on them, particularly agro-ecosystems where humans are heavily reliant on ecosystem resources for their livelihoods (Boko et al., 2007; Fischlin et al., 2007; UNDP, 2012). Appropriate, sustainable and proven technologies are needed for dryland communities and ecosystems to be resilient in the face of such challenges.

The International Panel on Climate Change (IPCC) Fourth Assessment Report stresses the serious need for adaptation strategies against climate change to be developed, especially in African drylands, as traditional coping mechanisms may not be sufficient (Boko et al., 2007). Additionally, the UK Government has committed to the Millennium Development Goals, including ensuring environmental sustainability. Reliable water supply is a key component of sustainability and development, and water supply is expected to be directly impacted by climate change (Boko et al., 2007; United Nations, 2012). Access to water is a focus area for the UK Department for International Development (DFiD) in its mission to actively support and promote global development (DFiD, 2012).

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 only a few small areas in south east Kenya, 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.

This research will lead to a greater understanding about the suitability of sand dams as a response to the expected impacts of climate change in drylands, specifically in dryland agro-ecosystems. The study takes place in the dryland valleys of Makueni, south east Kenya, a marginal agro-ecosystem. Makueni has experienced frequent and severe drought in recent decades, and conditions are analogous to those projected under climate change (Christensen et al., 2007; Fischlin et al., 2007).

In recent years the international community has turned its attention to adaptation responses to climate change (Schipper and Burton, 2009). Currently sand dams are promoted by only a small number of national and international NGO's, but it is timely to consider the usefulness of the wider application of sand dams as a relevant and appropriate technology for drylands in this policy environment.

Aims

The primary aim of this study is to test the hypothesis that *sand dams increase the adaptive capacity of drylands by increasing the resilience of vegetation through times of water scarcity.*

Objectives

Changes in vegetation can be measured by differences in the Normalised Difference Vegetation Index (NDVI), which is calculated from satellite images. 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;
3. To draw inference from results on the potential of sand dams as an adaptation response to climate change in drylands, including impacts on related measures such as Net Primary Productivity (NPP).

Limitations

Detailed knowledge of the study area, land use history and access to local climate records (if they exist), would greatly help in the validation of findings. Field studies would further validate findings since NDVI alone is unable to provide information about species composition and soil conditions.

The study of older dams over a longer period would increase understanding of the performance of sand dams in a range of climate conditions.

How this dissertation is arranged

Chapter One provides an overview and introduction to this research. In Chapter Two the literature applicable to this study is reviewed to outline the wider context for the work, the theoretical foundations that this work sits within, as well as previous work on the subject. Chapter Three describes the methods and sources. Chapter Four describes the results found. Chapter Five discusses the results in the context of the aims, objectives and the literature reviewed in Chapter 2, then critiques the study and suggests improvements. Finally, Chapter 6 summarises the conclusions, contributions to knowledge, and recommendations for future directions. References can be found immediately after Chapter 6 and detailed results are given in the appendices.

2. Literature review

In this chapter, firstly the context, global importance and characteristics of drylands are laid out, followed by the role of vegetation in provision of dryland ecosystem services. Then the impact of climate change on drylands, particularly drought, is reviewed as well as the theoretical framework of adaptation and resilience. The Normalised Difference Vegetation Index (NDVI) is then examined in relation to its suitability as an indicator of vegetation stress during drought, including related applications that can be derived from it. The body of literature on sand dams as an adaptation response to water scarcity is then reviewed; areas covered include the impact of sand dams on; groundwater levels, robustness under models of climate change, vegetation, and socio-economic indicators. Gaps in the currently body of knowledge are highlighted and how this study can contribute to understanding these gaps is discussed.

What are drylands?

Drylands are regions characterised by water stress because their average rainfall is less than the potential moisture losses through evaporation and transpiration. The United Nations Convention to Combat Desertification (UNCCD) describes this as the ratio of annual precipitation (P) to potential evapotranspiration (PET), and defines drylands as characterised by a P/PET of less than 0.05 to 0.65. Within this definition there are categories of Hyper-arid, Arid, Semi-Arid, and Dry Sub-humid. Table 1 below shows the range of P/PET values alongside average rainfall for each dryland category.

Table 1: Dryland categories and profile

Classification	Aridity Index (P/PET ratio)	Typical Rainfall (mm)
Hyper-arid	Less than 0.05	Less than 200
Arid	0.05 to 0.20	<200 (winter) to <400 (summer)
Semi-arid	0.20 to 0.50	200-500 (winter) or 400-600 (summer)
Dry Sub-humid	0.50 to 0.65	500-700 (winter)or 600-800 (summer)

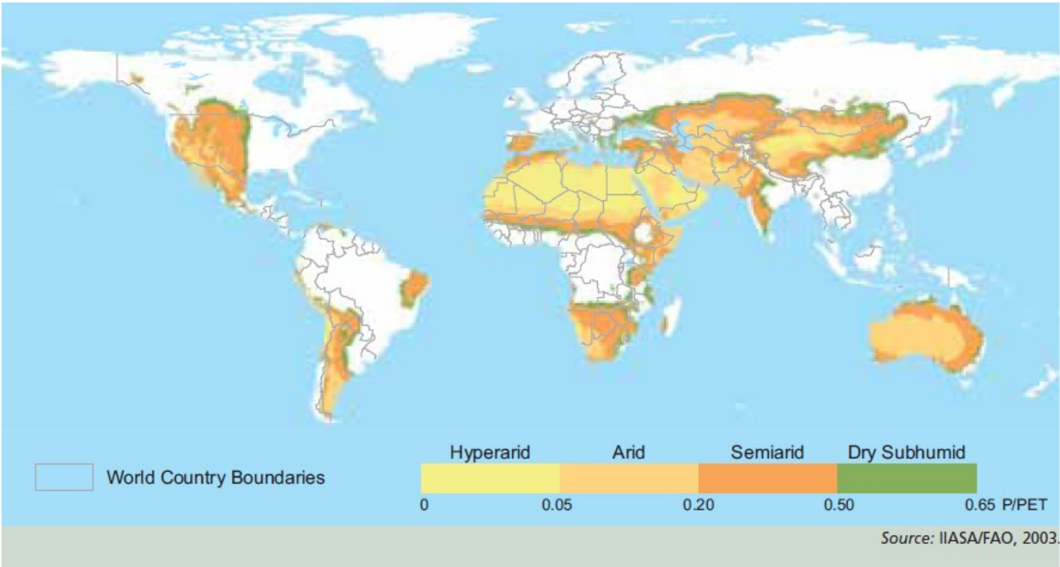
Source: FAO, 2004[1]

[1] FAO, 2004, http://www.fao.org/docrep/007/y5738e/y5738e06.htm#TopOfPage

Global importance of drylands

Drylands occur in every continent, although 72% occur in developing countries – which also house all of the most extreme examples (Safriel and Adeel, 2005). The most extensive areas of dryland are in Africa (Mortimore, et al., 2009). The distribution of the world's drylands is shown in Figure 1. Table 2 gives the percentage of global land area and population for each category.

Figure 1: Distributions of the drylands of the world



Source: IIASA/FAO, 2003[2]

Table 2: Land area and population of the drylands of the world

Classification	Global Land Area (%)	Population (%)
Hyper-arid	6.6	1.7
Arid	10.6	4.1
Semi-arid	15.2	14.4
Dry sub-humid	10.7	15.3
Total	**41.3**	**35.5**

Source: Safriel and Adeel, 2005, p.627

[2] IIASA/FAO, 2003, cited in Koohafkan and Stewart, 2008, p. 7

Characteristics of drylands

Drylands are characterised by highly variable, seasonal patterns of rainfall. Rainy seasons are typically short (3-4 months) and all the annual rainfall is delivered in intense storms over short periods, followed by long periods with no rainfall (8-9 months). Droughts are frequent and irregular (Millennium Ecosystem Assessment, 2005), although more severe droughts have occurred in the last decade than previously recorded (Zhao and Running, 2010).

Four major biomes exist in drylands including; desert, grassland, Mediterranean scrub, and forest (mainly woodland). A range of ecosystems can be identified within these four types (Safriel and Adeel, 2005). Dryland vegetation has evolved to typically have spatial patterns aligned with water availability and increasing aridity rather than pre-existing variables such as soil properties (Barbier, et al., 2006). Water is typically only available as rainfall or from seasonal rivers. Soils are characterised by low productivity due to low rainfall, and are often sandy with low fertility, little organic matter or nutrients. Human land use has closely evolved with the natural environment, and pastoralist or mixed agro-pastoralist livelihoods dominate land use types. Agro-ecosystems form a major component of drylands (Koohafkan and Stewart, 2008). Many dryland areas are degraded and recent estimates suggest that between 10 and 20% of deserts and drylands are degraded due to an imbalance between demand for and supply of dryland ecosystem resources (Adeel et al., 2005; Koohafkan and Stewart, 2008).

Impact of droughts

Drought in the context of drylands largely refers to meteorological drought, or where precipitation is below average for a period of time such that demand excels supply (Kundzewicz et al., 2007; Funk et al., 2012). Droughts that persist, or re-occur before systems have recovered, are called desiccation and drastically decrease land productivity (FAO, 2004).

In East Africa, the dynamics of vegetation strongly depend on water availability (Nicholson et al., 1990). Severe drought in East Africa in 2005 and 2006 resulted in crop failure and overgrazing, creating acute food insecurity in most parts of East Africa. Further drought episodes occurred in parts of Kenya, Somalia and Ethiopia in 2008-9 creating major food crises (Rulinda et al., 2012). The year 2011 was the driest on record with water scarcity extending into 2012 again causing major food security issues (FEWSNET, 2011).

Dryland ecosystem services

Despite their harshness, drylands provide valuable provisioning, regulating, supporting and cultural services to humans:

Provisioning services: Drylands supply food, fodder, fuel and construction materials. Agro-ecosystems within drylands support extensive rangelands. Major crops such as wheat, barley, sorghum, and millet originated in drylands and the genetic diversity present in drylands is important for global food security (WRI, 2012). Drylands food production systems provide 44% of the world's food supply (UNDP, 2012).

Regulating services: Although much land is degraded, the sheer extent of drylands means they carry out significant local and global climate regulation services. Drylands store large amounts of carbon, mostly in soils. Total dryland organic carbon reserves comprise 46% of the world's carbon reserves, 27% of which are in soils (Millennium Ecosystem Assessment, 2005). The fact that many dryland soils are degraded means they are not yet saturated and have potential to sequester much more carbon than they do currently (Faragae, et al., 2003; Trumper, et al., 2008). Examples of dry forests in the semi-arid lands of Mexico have been found to store more carbon than evergreen forests (Mortimore, et al., 2009).

Supporting Services: Soil formation and soil conservation partly form the basis of Net Primary Productivity since they determine soil moisture availability and nutrient cycling (Safriel and Adeel, 2005). These services are the foundation of biodiversity services since they result in the high functional diversity of plants, invertebrates and mammals found in drylands. Dryland biodiversity is relatively rich with eight of the 25 global ''biodiversity hotspots'' identified by Conservation International occurring in drylands (Safriel and Adeel, 2005).

Cultural Services: Drylands provide cultural services such as eco-tourism, and hold cultural, heritage, and spiritual values. For example, 13% of GDP in Kenya comes from dryland tourism (Mortimore, 2009) largely due to species diversity, especially of mammals.

The role of land cover in dryland ecosystem services

Land cover types, including cultivated land (agro-ecosystems), play a key role in dryland ecosystem services. Vegetation affects water availability to surface and groundwater aquifers and thus the amount of water available for ecosystem use (Sahin and Hall, 1996; DeFries, R. and Eshleman, K. N., 2004).

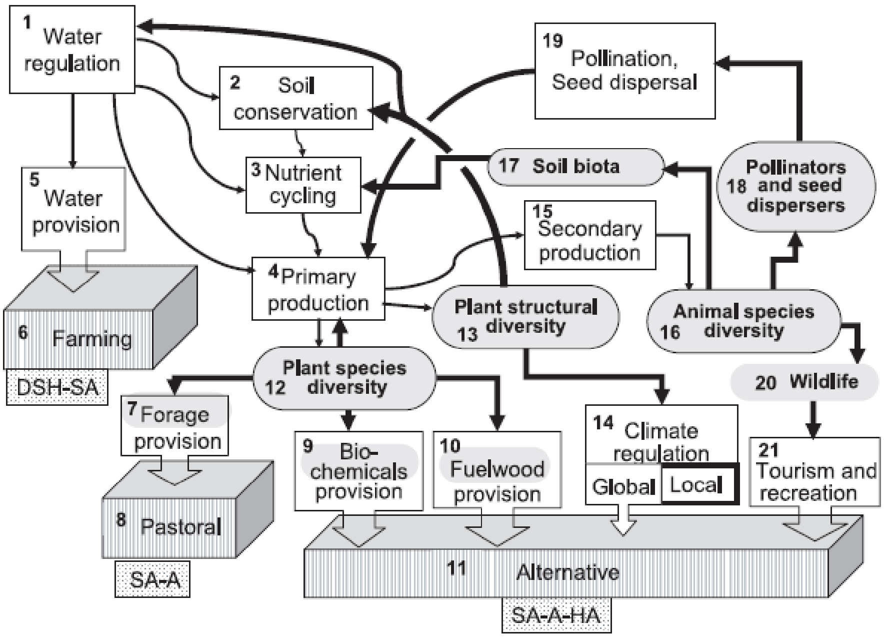
Plant structural diversity influences water retention by slowing runoff and providing catchment protection, which is of key importance since water is a critical limiting factor for biological productivity in drylands. Vegetation intercepts precipitation and recharges the aquifer rather than rainfall draining into river channels and away from where it fell. Water retention enables soil formation and conservation by encouraging slow infiltration of moisture into soils and facilitating the formation of organic matter (Safriel and Adeel, 2005). There is a consistent negative relationship between land cover and the amount of water in streams (Bosch & Hewlett, 1982).

Dryland vegetation regulates climate by reducing evaporation both during and after rainfall events at small and large scales. Vegetation creates microclimates through shading and affects the carbon balance through carbon fixation (Safriel and Adeel, 2005).

Plant diversity supports animal abundance and biodiversity since animals depend directly on primary production found in plant biomass to provide a variety of food sources and habitats (Safriel and Adeel, 2005).

Figure 2 shows the linkages between dryland types and livelihoods, their ecosystem services and the instrumental role of vegetation at the centre (‘Plant Structure and Diversity’ - see no.13).

Figure 2: Linkages between ecosystem services, biodiversity, livelihoods, and dryland subtypes



Legend

Rectangular boxes: Ecosystem services	*Thick arrows:*	*DSH: Dry sub-humid*
Rounded boxes: Components of biodiversity	*Involvement of biodiversity*	*SA: Semiarid*
Three dimensional boxes: Livelihoods	*Thin arrows: Direct*	*A: Arid*
Dotted rectangles: Dryland subtypes	*effects of services*	*HA: Hyper-arid*

Source: Safriel and Adeel, 2005, p.636

Additionally, several studies have related the importance of terrestrial vegetation cover and associated dynamic feedbacks on the physical climate (Christensen et al., 2007; Simoniello, 2008). Plant cover can alter the balance of energy at the earth's surface since plants intercept solar energy and convert it to carbon through photosynthesis, thus affecting the balance between sources and sinks (FAO, 2004; Running, 2004).

Human adaptation responses to water scarcity in drylands

Traditional adaptation responses to water scarcity

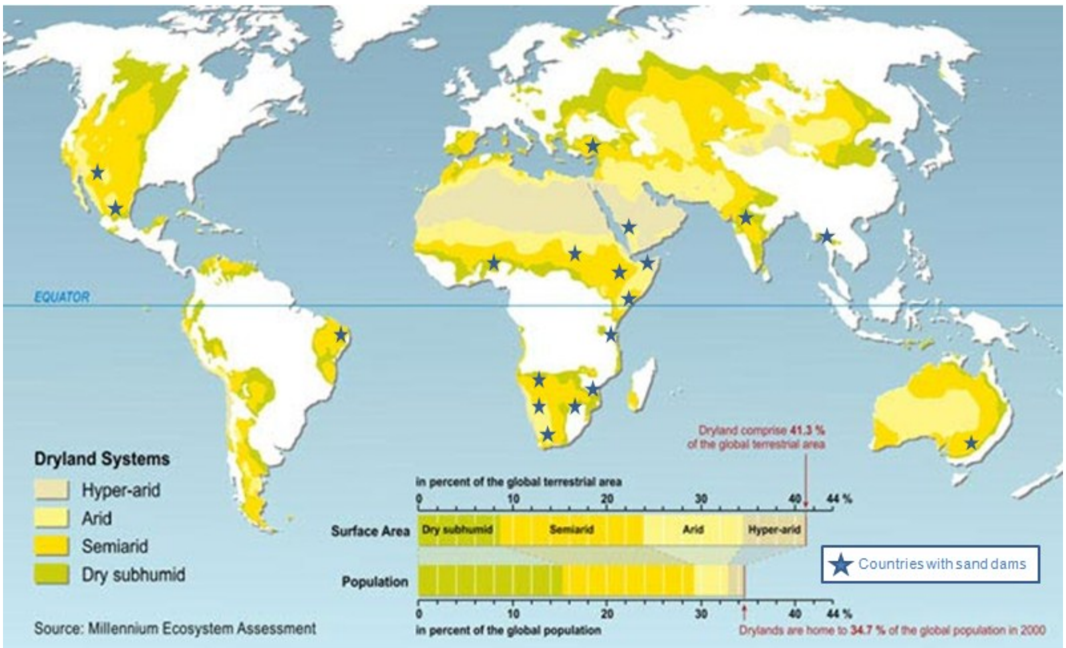
Rain water harvesting is an ancient technique traditionally used on a small scale by drylands peoples to overcome problems of water scarcity (Nilsson, 1988). Rain water harvesting structures intercept or obstruct the natural flow of rainwater in wet seasons and store water for drier periods (Hut et al., 2008). Rainwater can be retained before it hits the ground (as rain), or after (as either runoff or groundwater).

Water harvesting structures are thought to have been in use as long ago as 9000 BC. Runoff agriculture in the Negev desert, Israel, can be traced back as far as the 10th century BC. The grain production of the Roman Empire is thought to have been based on runoff agriculture. Water harvesting systems in Yemen date from 1000 BC and are still in use today (Oweis et al., 2001). Groundwater dams were used in Sardinia in Roman times (Nilsson, 1988).

Sand dams

Water can also be harvested and stored in sandy, seasonal river beds using sand dams (sometimes called sand-storage dams). Examples exist in Tanzania and more frequently in Namibia, but they are most commonly found in the drylands of south east Kenya (Nilsson, 1988) where communities of Ukambani people have built more than 1500 (Maddrell and Neal, 2012). The first Kenyan sand dams were built by a District Agricultural Officer (Eng. Classen) as part of the African Land Development Board (ALDEV) project. ALDEV constructed a range of earth dams, rock catchment dams, sand dams, boreholes and rangeland schemes in Ukambani from 1954 to independence in 1963 (Nissen-Peterson, 2006). Figure 3 shows the world distribution of sand dams today.

Figure 3: World distribution of drylands and sand dams

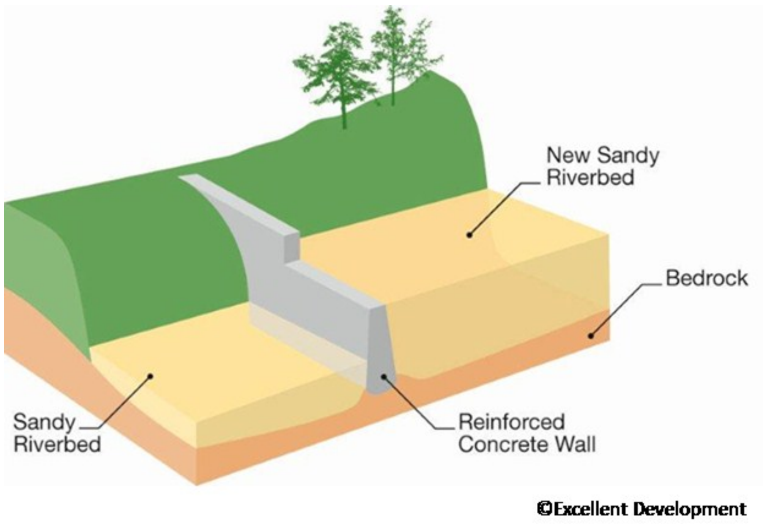


Source: Maddrell and Neal, 2012, p.26

What are sand dams?

A sand dam is a reinforced concrete wall built across a seasonal riverbed to harvest rainwater (see figure 4) for multiple uses including human consumption, small scale irrigation and livestock watering (Foster and Tuinhof, 2004; Hut et al., 2008).

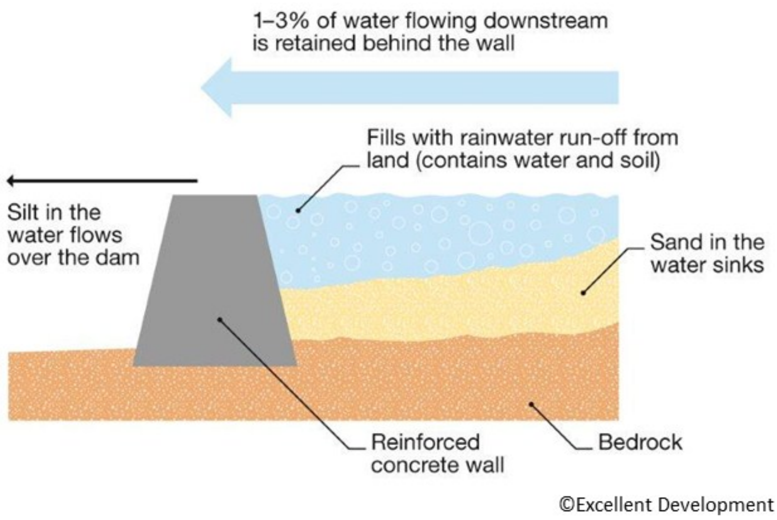
Figure 4: Placement of a sand dam in a river bed



Source: Excellent Development, 2011, p.8

The first seasonal rains fill the dam with water, silt and sand. The sand is heavier and so sinks behind the dam, but the silt and excess water wash over the top of the dam. Because the sand is porous, it holds water. When mature, the dam will be between 25-40% water (Maddrell and Neal, 2012).

Figure 5: Conceptual illustration of how a sand dam works



Source: Excellent Development, 2011, p.8

With each rainfall event the size of the sand reservoir increases allowing more water to be stored. Figures 6 and 7 below show a dam filled with water after its first seasonal rains, and a mature dam filled with sand, respectively.

Figure 6: A dam filled after the first season

Figure 7: A mature dam filled with sand

Source: Maddrell and Neal, 2012, p.20

The dam also obstructs groundwater naturally flowing through the permeable riverbed. This creates higher groundwater levels above the dam that subsequently infiltrate into the adjacent riverbanks, thus also raising groundwater levels in those riverbanks (Hoogmoed, 2007). The sub surface groundwater flows, and seasonal rains recharge the groundwater aquifer (Hoogmoed, 2007). Water can be extracted using wells or pumps placed on river banks close to the dam, or by using scoop holes in the sand reservoir (Quilis et al., 2009).

Sand dams are a simple, low cost way to provide and store water in drylands (Lasage et al., 2006; Tuinhof, et al., 2012). The sand shields the water from evaporation by the sun, contamination from animals, and water borne parasites such as mosquitoes (Guiraud, R., 1989, cited in Lasage et al., 2006; Aerts et al., 2007). Additionally, sand acts as a natural slow filter purifying the water (Huisman, and Wood, 1974), although the water quality from sand dams has yet to be systematically tested.

Crucially, anecdotal reports from Ukambani farmers suggest they maintain enough water in riverbanks to enable crops and natural vegetation to survive through the dry season and droughts (Excellent Development, 2012).

Adaptive capacity of drylands

Resilience and adaptive capacity

People and ecosystems have been adapting together and separately to the harshness of drylands for millennia. 'Social - ecological systems' are where these people and ecosystems intersect (Folke et al., 2010), and 'agro-ecosystems' are classic examples of mixed human - natural systems (Handmer and Dovers, 1996).

A key factor in successful adaptation is the rate of change occurring in an environment (Handmer and Dovers, 1996). However, climate change poses new risks outside the range of experience of many systems. Traditional coping mechanisms or adaptation strategies may not be sufficient to meet its demands (Adger et al., 2007; Boko, et al., 2007).

The International Panel on Climate Change (IPCC) Fourth Assessment Report defines adaptive capacity as the "ability or potential of a system to respond successfully to climate variability and change and includes adjustments in behaviour, resources, and technology" (Adger et al., 2007, p.727). It also says "Adaptation to climate change takes place through adjustments to reduce vulnerability or enhance resilience in response to observed or expected changes in climate and associated extreme weather events. Adaptation occurs in physical, ecological and human systems" (Adger et al., 2007, p.720).

Vulnerability is the ability or inability of individuals and systems to respond to any external stress placed on livelihoods and well-being, and in this context is largely concerned with political and socio - economic factors (Kelly and Adger, 2000).

Resilience is the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al., 2004, p1; Hollings, 1973). This definition emphasises the persistence of systems even in constant flux and instability, which aptly describes drylands since they are inherently unstable due to climatic extremes (Millennium Ecosystem Assessment, 2005; Mortimore, 2009). Resilience is different from stability as the latter refers to reversion to an original state (Hollings, 1973). Conway describes resilience in an equivalent term for agro-ecosystems as 'sustainability' where "sustainability is the ability of the system to maintain productivity following large disturbances" (Conway, 1986; Conway, 1987, cited in Handmer and Dovers, 1996, p. 191).

Impacts of climate change on drylands

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 (Sörensen et al., 2008).

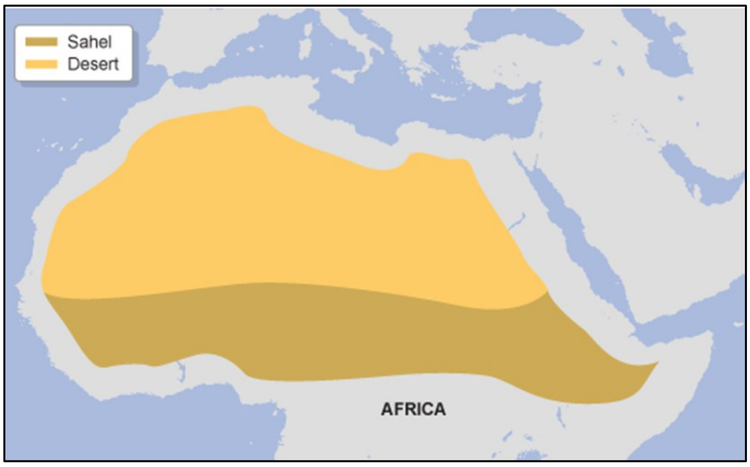
The IPCC 4th assessment suggests climate change will result in increased precipitation in Eastern Africa, but the weight of evidence suggests decreased precipitation is more likely. The IPCC regional projections indicated an increase of 5-10% precipitation in typical wet season precipitation due to an El Niño like climate (Christensen et al., 2007). However, observational data collected by the United States Agency for International Development (USAID) Famine Early Warning System Network reports that rainfall averages have decreased by 100mm over the last 50 years in Kenya. The IPCC projections also include warming in the Western Indian Ocean, which is supported by observational data. Warming in the Western Indian Ocean brings dry, subsiding air to the Greater Horn of Africa and acts to suppress rainfall. Recent La Niña years have been shown to have been drier and El Niño rainy seasons have tended more towards average, rather than the above-average rainfall expected (Funk, 2010). In summary this means that observational data suggests Kenya is getting warmer with less rainfall, resulting in a drying effect that will increase with further climate change (Funk, 2010).

Impacts of climate change on dryland ecosystems

The IPCC Fourth Assessment (2007) suggests dryland ecosystems is highly sensitive to climate change but that little is conclusively known about its impact due to the complex nature of multi - factor feedbacks (Fischlin et al., 2007). Direct CO_2 - fertilisation and the warming effect of rising atmospheric CO_2 could have contrasting effects on the dominant vegetation types. Regional changes in vegetation biomass due to increased CO_2 could affect local climates unequally. Uncertain, non - linear and rapid changes in ecosystem structure and carbon stocks are likely. On balance, drylands are expected to have less capacity for carbon sequestration due to greater soil respiratory losses as a result of higher temperatures, rainfall variability and changes to natural wildfire cycles (Fischlin et al., 2007).

The Sahel is a belt of dryland and a transition zone separating the Sahara Desert to the north and woodlands of the sub-Sahara to the south. It stretches across the north of the African continent between the Atlantic Ocean and the Red Sea (see figure 8). The Sahel experiences extreme drought and Sahelian dryland vegetation response to climate variation has been the subject of wide ranging academic investigation. Findings from research on the Sahel are relevant to this study since parallels can be drawn with dryland ecosystem processes in south east Kenya, some of these are given in the next section on NDVI.

Figure 8: The Sahel Region, North Africa



Source: BBC, 2012[3]

Additionally, an analogy can be drawn between Sahelian ecosystem responses to past periods of rainfall variability and future climate change impacts, given that the areas affected by extreme drought, like the Sahel, are expected to increase globally from 1% to about 30% by the 2090's (Burke et al., 2006; Fischlin et al., 2007). This study draws from this knowledge and takes the approach of using drought as an analogue to climate change to understand whether sand dams increase resilience to drought in dryland agro-ecosystems.

Impacts of climate change to drylands people

Agro-ecosystems in the drylands of Africa have low adaptive capacity and high inherent exposure to climate change due to geography. Farmers and ecosystems currently have low resilience to climate

[3] Source: BBC, 2012
http://www.bbc.co.uk/schools/gcsebitesize/geography/weather_climate/weather_human_activity_rev6.shtml

shocks such as drought (Boko et al., 2007), and high vulnerability due to reliance on rainfall for economic and social development (Mutuku, 2012).

The possible consequences of the combination of higher temperatures and more variable rainfall means dryland agricultural systems are likely to become increasingly marginal (Thornton, 2006, cited in Boko et al., 2007). This would mean reduced crops and pasture growth, contributing to increased desertification, food insecurity and livestock loss. Crop failure rates in East African mixed rain-fed dryland systems could increase from nearly one in six years to one in three years (Jones and Thornton, 2009). The adaptive capacity of the dryland pastoralists, smallholder and subsistence farmers may be overstretched, leading to increased poverty and unsustainable coping strategies (Sörensen et al., 2008).

Drought is a major exposure risk to crops and the ability to manage for it is crucial. Technology that is appropriate for climate change scenarios is one way to increase resilience and decrease vulnerability of natural and human systems, and increase their adaptive capacity (Boko et al., 2007; Adger et al., 2007).

Suitability of the Normalised Difference Vegetation Index (NDVI) as an indicator of vegetation stress during periods of water scarcity

What is NDVI?

Vegetation growth is frequently limited by lack of water, thus the relative density of vegetation is a good indicator of drought (Weier and Herring, 2012). NDVI is the most commonly used index for vegetation density. NDVI is based on the principle that varying surface types reflect distinct wave-lengths of light differently, which is derived from satellite images.

Visible light is absorbed by the chlorophyll (photosynthetic pigments) in plant leaves, but the cell structure of leaves strongly reflects near-infrared light (Weier and Herring, 2012). Figure 9 shows how a healthy (more leafy) plant will therefore absorb more visible light and reflect a large portion of the near-infrared light. Conversely, unhealthy or sparse vegetation reflects more visible light and less near infra-red light (Weier and Herring, 2012). This reflectance information can therefore be used as a proxy for plant biomass.

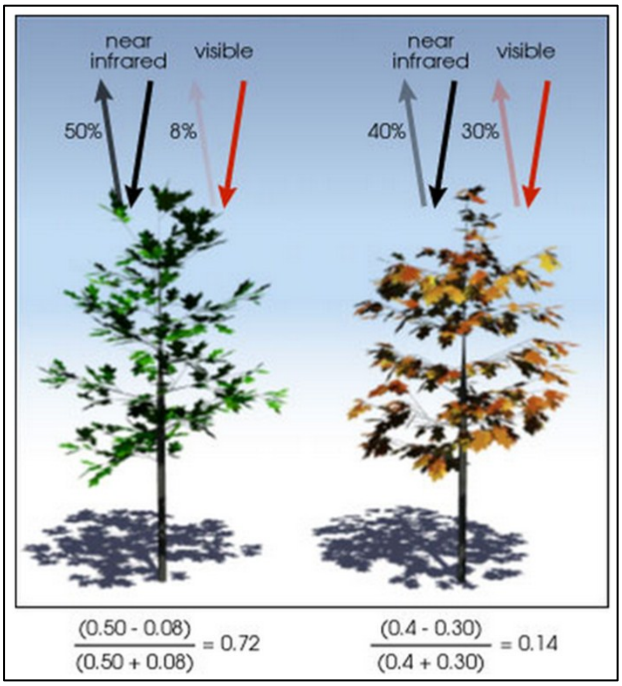


Figure 9: Spectral reflectance of healthy and unhealthy vegetation

Healthy vegetation (left) reflects greater infrared and less visible wavelengths giving higher NDVI values, whereas unhealthy vegetation reflects the opposite, resulting in lower NDVI values.

Source: Weier and Herring, 2012.[4]

NDVI is calculated as the normalized difference of the spectral reflectance of the near infrared (NIR) wavelength channel and the red visible channel (RED): NDVI = (NIR - RED)/ (NIR + RED) (Running et al., 2004)

NDVI values vary between -1 and +1. Values for vegetated land areas generally range from approximately 0.1 to 0.7. Where they fall between zero and 0.1 land cover is generally sand, rocks, or bare/sparsely vegetated soil. Values of between 0.2 and 0.3 are generally grass and open shrubland; values between 0.3 and 0.5 are generally wooded grass and shrubland (savannah) (De Fries et al., 1998; Weier and Herring, 2012). Values greater than 0.5 indicate dense vegetation (Rulinda et al., 2012).

NDVI as an indicator of drought

Although NDVI is specifically a measure of photosynthetic activity, it has been shown to be highly correlated with parameters of plant health and productivity which are in turn highly correlated with water availability. Therefore NDVI is often used as an indirect indicator of drought (Singh et al., 2003; Ji and Peters, 2003, Rulinda et al., 2012; Pettorelli et al., 2005).

[4] Weier and Herring, 2012, http://earthobservatory.nasa.gov/Features/MeasuringVegetation/printall.php

A detailed analysis of region wide NDVI records for the Sahel 1981 – 2003 showed that NDVI was strongly coupled with rainfall (Anyamba and Tucker, 2005). Negative NDVI values were present during the 1980's, a period of extreme drought. Values increased as rainfall returned to the region and a relative 'greening' occurred as vegetation recovered in following decades (Anyamba and Tucker, 2005). Subsequent analysis of the same period, however, has shown that this response is not uniform and there is likely to be a complex interplay between the effects of human land use and climate variability on dryland environments (Rasmussen et al., 2001). Additionally, although NDVI can accurately show greening effects, it cannot determine a return to prior species composition, ecosystem structure or function, nor surface soil conditions (Pettorelli et al., 2005).

Other limitations of NDVI are around the impacts of cloud cover, saturation in dense canopies and sensitivity to soil reflectance. A number of derivatives and alternatives to NDVI have been developed to minimize these issues; the two main ones include the Soil-Adjusted Vegetation Index (SAVI) and the Enhanced Vegetation Index (EVI). SAVI accounts for the reflectance influence of sparsely vegetated soils, but requires local calibration for soil types. EVI accounts for atmospheric influence and saturation in dense canopies, but it can only be used with MODIS satellite data which is at a spatial resolution of 250m by 250m for vegetation indices (Pettorelli et al., 2005). However, despite its shortcomings NDVI is the most widely used and oldest vegetation index that has consistently and reliably been used for application in vegetation time series analysis (Herrmann et al., 2005).

Many agencies use NDVI as a relative measure of biomass for drought monitoring purposes so as to be better prepared for emergencies and to help plan recovery programmes. The United Nations Food and Agriculture Organization (FAO), Africa Real Time Information Systems (ARTEMIS), and the USAID Famine Early Warning System (FEWS) programmes all use low resolution (1km by 1km) NDVI images derived from the NOAA-AVHRR satellite imagery for use in famine early warning systems (Eastman, 2012). The Kenyan government's Arid Lands Monitoring Project uses NDVI as an indicator of severity of drought, and they report a statistically significant negative relation between NDVI and food aid required by Kenyan dryland populations (Johnson and Wambile, 2011). Brown et al. (2006), has shown the relationship between NDVI, food prices and drought severity in West Africa.

To understand the severity of drought, the difference between the long term average NDVI and the NDVI of the period of drought under study is measured. The difference gives the 'difNDVI' value which is an indication of the degree of water stress on vegetation. If the difference is positive, vegetation is above average and healthy. Zero values indicate no change and negative difNDVI values suggest vegetation stress caused by water scarcity or drought conditions (Song et al., 2004, cited in Rulinda et al., 2012). In this study difNDVI is based on the long term NDVI for the Kenyan Arid lands, as measured by the Government of Kenya Arid Lands Project, to give context to the severity of drought at sand dam and control sites (Arid Lands Resource Management Project II, 2009).

NDVI and Net Primary Productivity

Ecosystem functional types or biomes can be differentiated from NDVI through the definition of land cover classes (Tucker et al., 1985; De Fries et al., 1995; De Fries et al., 1998; Pettorelli et al., 2005). This enables quantification of Net Primary Productivity (NPP) at various scales, since much work has been done to establish the typical NPP of different biomes from both field studies and remotely sensed imagery (Running et al., 2004). NPP is an important part of the carbon cycle; it represents the amount of carbon retained by plants after photosynthesis and respiration. It is useful because it is an indicator of variation in the amount of carbon that is fixed by plants, and therefore carrying capacity of the land in terms of amount of potential yield from crops, pasture and wood (Unganai and Kogan, 1997; Zheng et al., 2003).

NPP has been shown to be well correlated with NDVI (Sellers, 1987, cited in Running et al., 2004; Prince and Goward, 1995; Running et al., 2004) and remotely sensed indices have been successfully integrated with extensive data sets of credible ground measurements to compile a single table of mean NPP values for different biomes (Zheng, 2003). The occurrence of drought has been connected to a reduction in NPP in a study of global terrestrial NPP over the last decade using NDVI (Zhao et al., 2010). This is relevant because NPP is an indicator of potential yield and thus a general index of crop productivity (Running et al., 2004), thus levels of NPP affect vulnerability and adaptive capacity in agro-ecosystems.

Although outside the scope of this study, another useful application of NDVI is estimation of the amount of carbon that can be stored, or sequestered, in a terrestrial system (Running et al., 2004).

Sand dam research

The body of academic literature on the potential for sand dams as an adaption response to climate change is slim. There are only a small number of scientific studies on sand dams per se, the majority of which focus on hydro-geologic process modelling of groundwater storage, flows, and their effect on the water balance. Two studies look at impacts of sand dams on vegetation specifically, and a small number of studies look at the socio-economic impacts of sand dams on communities. These works are discussed briefly in relation to this study below.

Hydro-geological studies

Impacts of sand dams on groundwater levels

Groundwater level affects the amount of water stored in the soil and impacts rates of evaporation, groundwater recharge, and runoff. Groundwater influences the amount of soil moisture available to plants and therefore their health and productivity (Compagnucci et al., 2001). The first systematic measurements to understand groundwater flows and storage around sand dams and how this affects groundwater levels were carried out by Borst and de Haas in 2005 on a small number of sand dams in south east Kenya (Borst and de Haas, 2006).

Impact on storage and runoff

Raised groundwater levels were found at sand dam sites and attributed to an increase of storage in riverbanks by 40% due to sand dams (Borst and de Haas, 2006; Jansen, 2007; Hoogmoed 2007). This increase in storage results in a reduction in runoff at sand dam sites roughly equivalent to the amount of the increase in storage in the riverbanks (Jansen, 2007).

Impact on flow

The amount of flow removed from the river by a sand dam is only around 2% of the total flow, of which 1% would be stored naturally by a sand riverbed anyway (Borst and de Haas, 2006). Later modelling efforts suggest this estimation could be refined to 1.8% for the April-May rains, and 3.8% for the October-December rains (Aerts et al., 2007). The low figures are significant because they implies there is no or little effect on downstream users or ecosystems, although Aerts et al., (2007) caution that the figures are based on optimistic flows and may not reflect reality in dry years or drier catchments.

Impact on groundwater recharge

The rate of groundwater recharge after rain is important in the recovery rate of vegetation after stress. The sand reservoir behind a sand dam fills within days of the first rains, remaining throughout the season, and the river banks subsequently fill within a month of the first rains as groundwater accumulates in the aquifer (Borst and de Haas, 2006; Hut et al., 2008; Quilis et al., 2009). After the first rains the groundwater aquifer is recharged completely and the river starts and continues to flow, suggesting that refilling of larger aquifers does not reduce flow downstream of the dam (Hut et al., 2008).

Impact on upstream vs. downstream aquifers

Groundwater level is estimated to be about 2m higher upstream of the dam directly after rain compared to downstream. The water level downstream of the dam decreases faster compared to upstream (Hut et al., 2008). However, it is likely that downstream effects are likely not well modelled (Hut et al., 2008) and later studies suggest that groundwater levels increased both upstream and downstream by 100 cm and 80cm respectively (Quilis et al., 2009). Anecdotal evidence suggests that the impact is both upstream and downstream when dams are mature (Hut et al., 2008).

Impact of distance between sand dams

Quilis et al., (2009), modelled a range of distances between dams and found that where the zone of influence of sand dams overlapped (a distance of up to 500m) storage capacity per dam decreases, but groundwater levels across the catchment increase.

Impacts on storage through the dry season

Once groundwater levels have recharged, they reduce slowly through the year thus providing increased water availability to vegetation through dry seasons and drought (Borst and de Haas, 2006; Hoogmoed, 2007; Hut et al., 2008; Quilis et al., 2009). A survey of 137 households in Kitui found that sand dams increase the amount of water that was able to be used and stored in the dry season by 2.5 months (Pauw, et al., 2008).

Sand dams as a response to climate change

The performance of sand dams was modelled under the A2 scenario of the IPCC Fourth Assessment Report (2007) and found to have a greater impact on downstream users than in current conditions (Aerts et al., 2007). In the A2 situations of increased frequency of water shortages, greater variability of rainfall and runoff, higher evaporation rates and increased consumption, the amount of flow taken from the river increased from 1.8% to 11% in the April-May rains, and from 3.8% to 60% in the October - December rains (Aerts et al., 2007). However, these findings had caveats that further research was needed to better understand spatial variation of rainfall distribution under climate change, dynamic groundwater storage, recharge processes and flows around dams (Aerts et al., 2007; Quilis et al., 2009). Moreover, research on additional water consumption and availability trends under increased populations and climate change is required (Aerts et al., 2009).

However, the increased variability in rainfall projected under climate change may play to the advantage of sand dams. The recharging of sand dam aquifers happens quickly, over the course of short, intense rainfall events (Borst and de Haas, 2006; Hut et al., 2008, and Quilis et al., 2009) which are likely to become more common in drylands with climate change (Christansen et al., 2007).

Limitations of the hydro-geological studies are that they are heavily reliant on models based on measurements from a small number of dams over relatively short periods of time (3-18 months). Subsequently, the performance of sand dams over extended or consecutive periods of drought is not confidently known.

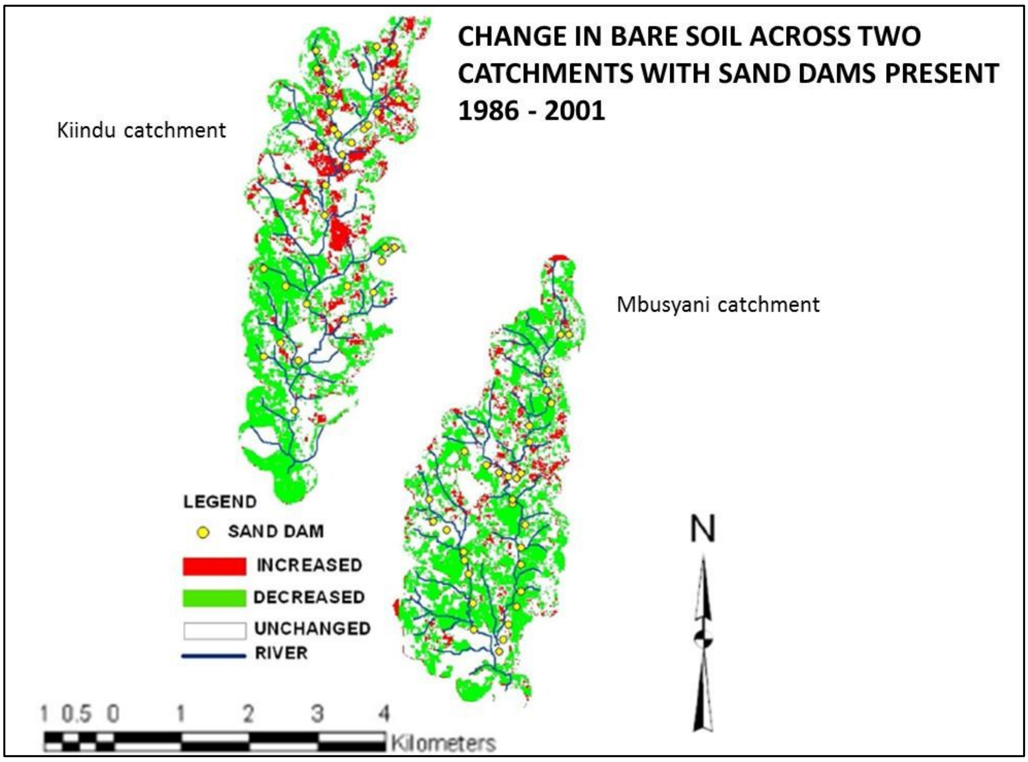
Impact of sand dams on NDVI

Only one study is known that relates the impacts of sand dams to NDVI, and is part of a wider piece of work on the impacts of sand dams on runoff. The study showed that NDVI at sand dam sites largely mirrors the growing season, with NDVI increasing after seasonal rains and decreasing towards the end of the growing season. High levels of productivity were recorded throughout the season with NDVI values of 0.44 to nearly 0.8 (Jansen, 2007). This study is helpful in that it provides context to the hydro-geological studies by showing that NDVI at sand dam sites is aligned with seasonality through the growing season, and can therefore act as baseline information for non-drought periods. However, NDVI was derived from low resolution satellite images (250m x 250m) which is low for the small scale of sand dams. Moreover, the extent to which this effect occurs at sites without sand dams is not known.

Impact of sand dams on land cover

Sand dams have been found to 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 (Manzi and Kuria, 2011). Figure 10 below shows the results of a land cover detection analysis in south east Kenya. Two catchments, both with sand dams, were compared between dry seasons in 1986 and 2001 using supervised classification of satellite images. The change in vegetation for both catchments was an increase of between 43% and 52%. The increase in vegetation is shown in green; the increase in bare soils (due to cropping) is shown in red. Areas of no change are shown in white.

Figure 10: Change in vegetation at two sand dam catchments 1986 to 2001.



Source: Manzi and Kuria, 2011[5]

The increase in vegetation is suggested to be due to Borst and De Haas' 2006 findings that sand dams increased groundwater levels, and that these higher levels were maintained over dry seasons (Manzi and Kuria, 2011). The increased groundwater levels are also suggested to have modified soil moisture regimes, prompting plants to germinate, grow and reproduce causing changes in the structure of riverbank plant communities (Jacobsen et al., cited in Manzi and Kuria, 2011), although it was noted that NDVI and soil moisture studies are required to confirm this (Manzi and Kuria, 2011).

This land cover change detection analysis is important since it is the only study to consider impacts before and after sand dams were built, and is the largest sample of dams studied thus far. However,

[5] Manzi and Kuria, 2011, p. 145

because there are no controls it is difficult to know if the change is due to the presence of sand dams or due to regional climate patterns. At the time of both samples, Kenya was recovering from discrete, severe droughts, thus the similarities in conditions at the time of sampling would seem to corroborate results. However, Conway (2008) discusses how in the 1980s, 1990s and 2000s, the East Africa region as a whole was recovering from a period of severe desiccation in the 1970s. He then goes on to describe the mid-1980s to 2000 as a period of "relative stability punctuated by extreme wet years in East Africa" (Conway et al., 2008, p.1). In Conway's scenario we could expect land cover classes to undergo a relative 'greening', much like the greening of the Sahel from 1980 to 2000 (Anyamba and Tucker, 2005), and vegetated land classes to become more common regardless of whether or not sand dams existed. Moreover, spatial variability in rainfall, such as local rains can have a significant effect on vegetation from site to site. The contrasting views in the literature highlight the importance of accounting for the influence of regional scale climate trends with controls, and having a representative temporal sample.

Socio - economic impacts

Sand dams have been shown to reduce vulnerability of dryland farmers by raising the incomes of farmers near dams by more than 60% (Lasage et al., 2007). In detailed surveys of the social and economic effects of sand dams in south east Kenya, it was found that sand dams reduced the amount of time required for water collection and increased the time respondents had available to spend on income generating activities (Mutuku, 2012). Sand dams made a positive difference to the range and degree of economic activities carried out in the study area. Sand dams provided access to irrigation, meaning crops could be diversified and non-agricultural activities could be taken up such as brick making (Pauw et al., 2008). Moreover, the income of households with access to sand dams increased through drought periods, whereas incomes of households without access to sand dams decreased (Pauw et al., 2008).

Interestingly, sand dams were also found to create more time to carry out cultural and community activities, for example religious activities and 'Harambee' a tradition where community members help each other achieve communal goals. Importantly, it was found that sand dams increased school attendance since children either spent less time looking for water themselves, or less time looking after their siblings whilst their mothers were looking for water (Mutuku et al., 2012).

Table 3 below summarises a range of socio-economic benefits of sand dams found by Rempel (2005), Lasage (2006) and Pauw (2008) by Aerts et al. (2008). Of note is the time saved on fetching water of an average of 100 minutes per day.

Table 3: Summary of socio - economic benefits of sand dams in Kitui, south east Kenya

Indicator	With dam	Without dam
Less months of primary water source depletion	2.5	-0.2
Change in distance to primary water source	-2016 m	+23 m
Change in water use	3.44 X more	0.96 X less
Daily time saved on fetching water	100 minutes	-7 minutes
Newly irrigated land	+0.18 Ha	-0.01 Ha
New fruit trees	13	5
Change in income (€/year)	+270	-380
Malnutrition	decreased	increased

Source: Aerts et al., 2008, p.1

Summary of the main themes of the literature reviewed

Vegetation plays an important role in the provision of ecosystem services. Resilience to drought in agro-ecosystems is key to the continued provision of these services under climate change conditions. Hydro-geological models suggest sand dams are a way to increase groundwater (Borst and de Haas, 2006; Jansen, 2007; Hoogmoed, 2007; Gijsbertsen, 2007; Aerts et al., 2007; Hut et al., 2008; Quilis, 2008; Quilis et al., 2009) thus enhancing the resilience of vegetation to drought at sand dam sites. Whilst this has not yet been demonstrated empirically, studies of the impact of sand dams on land cover go some way to validate this assumption. Additionally, studies of socio-economic factors provide some evidence for improved adaptive capacity due to sand dams (Lasage et al., 2006; Lasage et al., 2007; Pauw et al., 2008; Mutuku, 2012).

My research aims to test the hydro-geological findings and assumptions with empirical NDVI data about the health of vegetation through periods of water scarcity. Based on the hydro-geological models this vegetation health would be expected to be improved at sand dam sites due to the additional water stored in sand dam reservoirs and riverbanks, thus providing a buffer to vegetation through drought.

3. Methods

This chapter covers the methods and sources used; it explains why these methods were chosen in the context of the literature review and the aims and objectives of the study, so that the results may be interpreted correctly by the reader.

Methods overview

A literature review was carried out to ascertain what is already known about sand dams as an adaptation response to climate change, and what questions of value are outstanding. Additionally the literature review helped to determine the most appropriate methodology and the sampling strategy.

This research is a quantitative study. Satellite images were collected and analysed for NDVI data to test for differences in vegetation between samples and controls, using remote sensing techniques and inferential statistics.

This method was largely chosen because of the availability of historical satellite images since there is little baseline data about vegetation available for the study area. Historical data is necessary to analyse the performance of sand dams in time of past water scarcity.

Potential alternative methods

A range of alternative methods were considered for the study. Their advantages and disadvantages and reason for exclusion are given in table 4 (no. 1 to 6) along with the method that was selected (no. 7).

Table 4: Matrix of potential alternative methods, and selected method

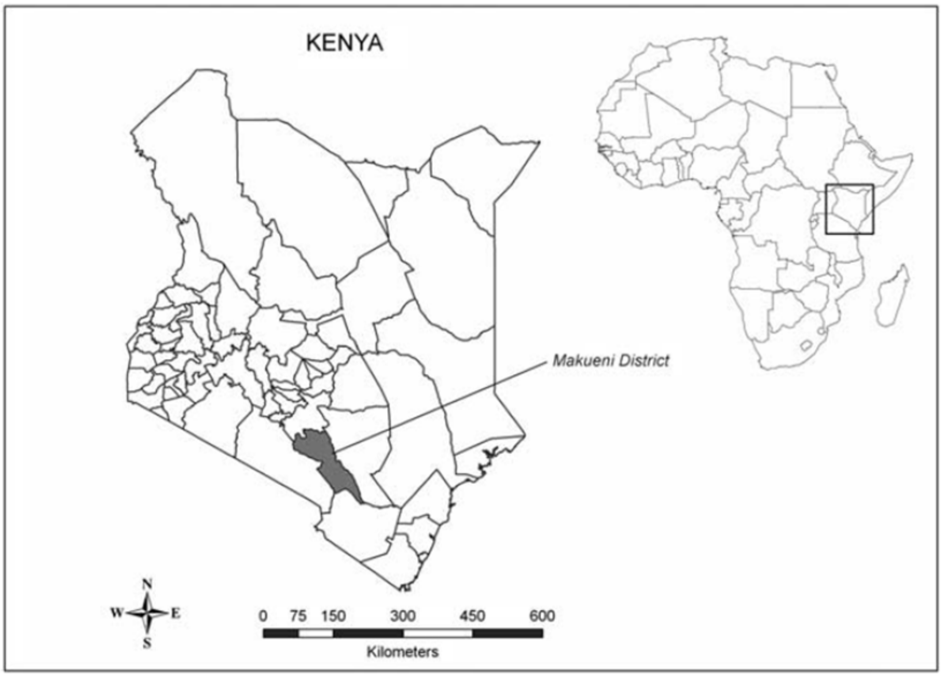
	Method	Advantages	Disadvantages	Decision and Reason
1	Land cover change detection analysis before and after sand dams were built, with controls	Better understanding of effect on ecotypes, land use, species and soil composition	Requires detailed field studies and baseline data for the study area	Not selected: Resources not available for detailed field studies, baseline data not known to be available
2	*Analysis of aerial/ other photographs before and after sand dams built, with controls*	Better understanding of effect on ecotypes, land use, species and soil composition	Data not known to be available for the study area	Not selected: Data not known to be available
3	Field based comparison of sites before and after sand dams were built, with controls	Better understanding of effect on ecotypes, land use, species and soil composition	Baseline data for past periods not known to have been collected/available	Not selected: Baseline data not known to have been collected/available
4	Social survey of farmers and the impact of sand dams on their lives	Greater insight into social resilience and impact of sand dams on communities	Extensive time in field required. Large sample size required to identify effects	Not selected: Some socio-economic data already exists that can be leveraged. No budget for extensive field based survey
5	SAVI[6] analysis of sand dam and control sites through drought periods	More accurate readings where there are significant areas of bare soils	Field studies required in order to calibrate for different soil types	Not selected: Resources not available for detailed field studies
6	EVI[7] analysis of sand dam and control sites through drought periods	EVI corrects for limitations of NDVI, Landsat 7 images not used so no issues of missing data	Compatible with MODIS images only – but resolution too low for a sand dam study	Not selected: Spatial resolution of MODIS images too low for study of sand dams
7	NDVI analysis of sand dam and controls over drought periods	Satellite images available at suitable spatial and temporal scales	No insight into performance of vegetation before dams built	**Selected** : Meets aims of study, feasible within time and resource constraints

[6] Soil Adjusted Vegetation Index
[7] Enhanced Vegetation Index

Introduction to the study area

The study sites are located in Makueni District, south east Kenya (see figure 11). Makueni District lies between latitudes 1°35'S and 3°S and longitudes 37°10'E and 38°30'E and covers an area of 7,966km^2. It has a population of 884,557 as per the 2009 census, and an annual population growth rate of 2.4% (Kenya National Bureau of Statistics, 2010). More than 60% of the population live below the poverty line (Commission on Revenue Allocation, 2012).

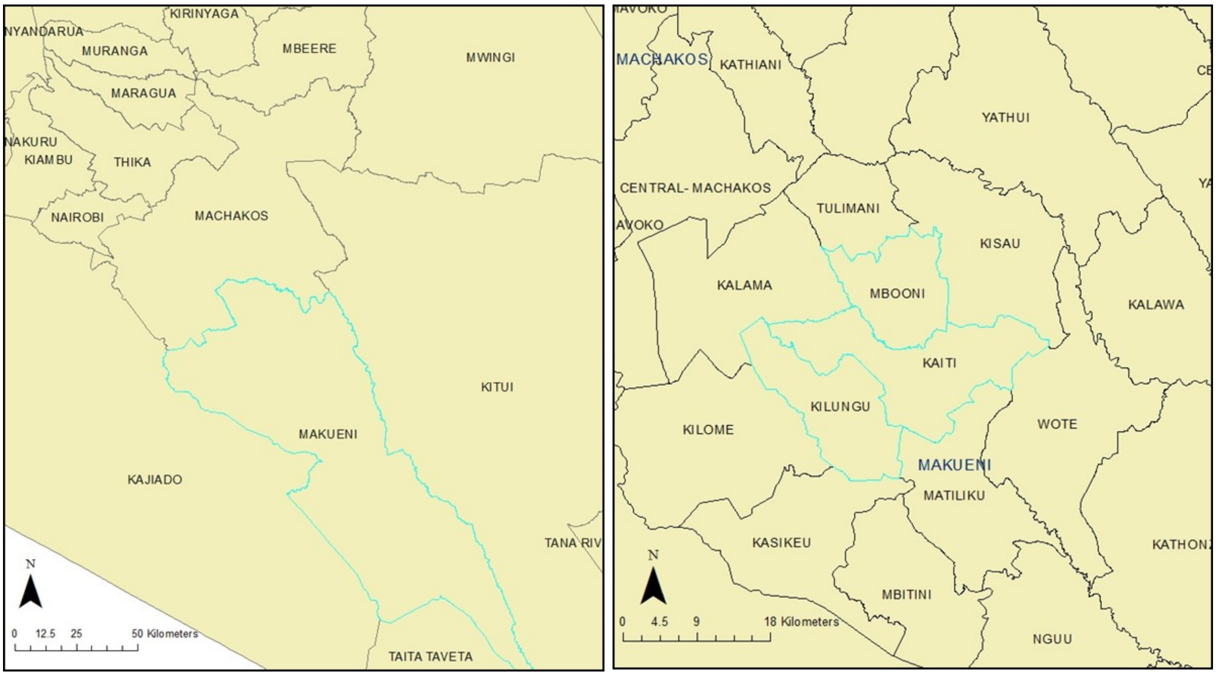
Figure 11: Study area – Makueni District in the Kenyan and African context



Source: Speranza, 2010, p.627

The study area falls in three of the northern administrative Divisions of Mbooni, Kaita and Kilungu (see figure 12), which also have the highest population densities of 140-200 people per square kilometre (Commission on Revenue Allocation, 2012).

Figure 12: Boundaries of Makueni District (left) and Divisions where study area is located (right)



Source: ESRI et al.a.[8]

Sample sites are in the Nzaaya Valley which falls on the Mbooni and Kaita Division borders with one example in the Kalama Division. For this study the Kalama example is grouped with Mbooni since it is very close to its border and has similar characteristics. Control sites are in the upper Kitandi Valley which is in the Kilungu Division.

All three of Mbooni, Kaita and Kilungu Divisions occur in hilly terrain between 1100 and 1900m above sea level. The overall drainage pattern is from west to east. Mbooni and Kilungu Hills have a few perennial streams (Arid Lands Resource Management Project II, 2009), but the area is dependent on seasonal rivers for drinking water and agriculture (Mutuku, 2012).

The climatic zone for both sand dam and control sites is dry sub - humid, with a PET of 0.65 (FAO, 2005). The study area has a bimodal rainfall distribution driven by the north-south movement of the Inter Tropical Convergence Zone (ITCZ). The bimodal pattern consists of the 'Short Rains' that generally run from October to December and the 'Long Rains' that run from March to May. Annual rainfall is typically 800-1200mm per year but both the seasonal and the annual rainfall totals vary widely and drought events follow cycles of four or five years, normally in runs of two or more

[8] ESRI et al.a., Eastern Africa: Administrative Boundaries Kenya, Districts and Divisions

seasons (Tiffen et al., 1994). Droughts, dry spells and their variability have been associated with the El Niño Southern Oscillation (Ambenje, 2000). The mean temperature over Makueni District ranges from 20.2°C to 24.6°C averaging at 22.1°C (Arid Lands Resource Management Project II, 2012).

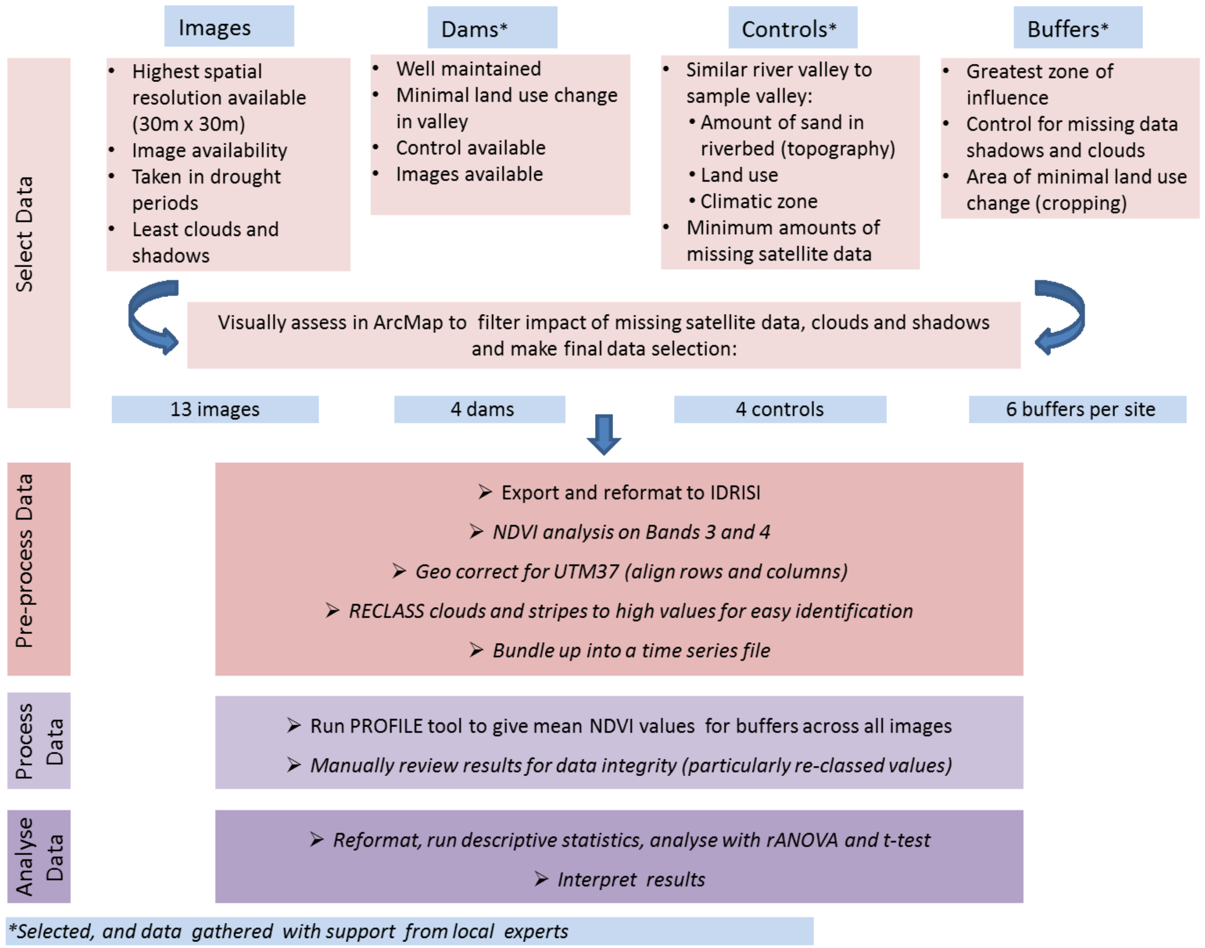
The main land cover type is cropland, with small pockets of bush and woodland, savannah and grassland (FAO 2000, cited in World Resources Institute, 2007). The main food crops grown are maize, beans, cowpeas, pigeon peas, sorghums and mung beans, with a significant reliance on maize, while the main livestock species kept are cattle, goats and poultry (Kenya Food Security Steering Group, 2011). Soils are of low fertility, generally formed of red clays, sandy clay loams to sandy clays (Jaetzold et al., 2006; Speranza, 2011; Claessens et al., 2012; Kenya Food Security Meeting, n.d).

Environmental degradation has occurred in parts of the county in the past due to the felling of trees for charcoal burning and firewood, and harvesting of sand from rivers, exposing large tracts of land to water and soil erosion. Land is classed as marginal for agricultural activities which are entirely rain fed (FAO 2000, cited in World Resources Institute, 2007). Subsistence oriented crop farming and livestock-keeping are the major livelihoods (Speranza, 2010; Claessens et al., 2012). The district has a deficit of food supply compared to demand, food production is low and fluctuates due to unreliable rainfall. Since 2004 the district has experienced near consecutive partial to total crop failures due to poor rainy seasons (Kenya Food Security Meeting, n.d.).

Sample and analysis strategy

A simplified view of the sampling and analysis strategy is given in figure 13 below. This strategy followed four stages; selection of data, pre-processing, processing, and analysis, each of which is described in the next section.

Figure 13: Flowchart of sampling and analysis strategy



Selection of data

Selection of satellite images

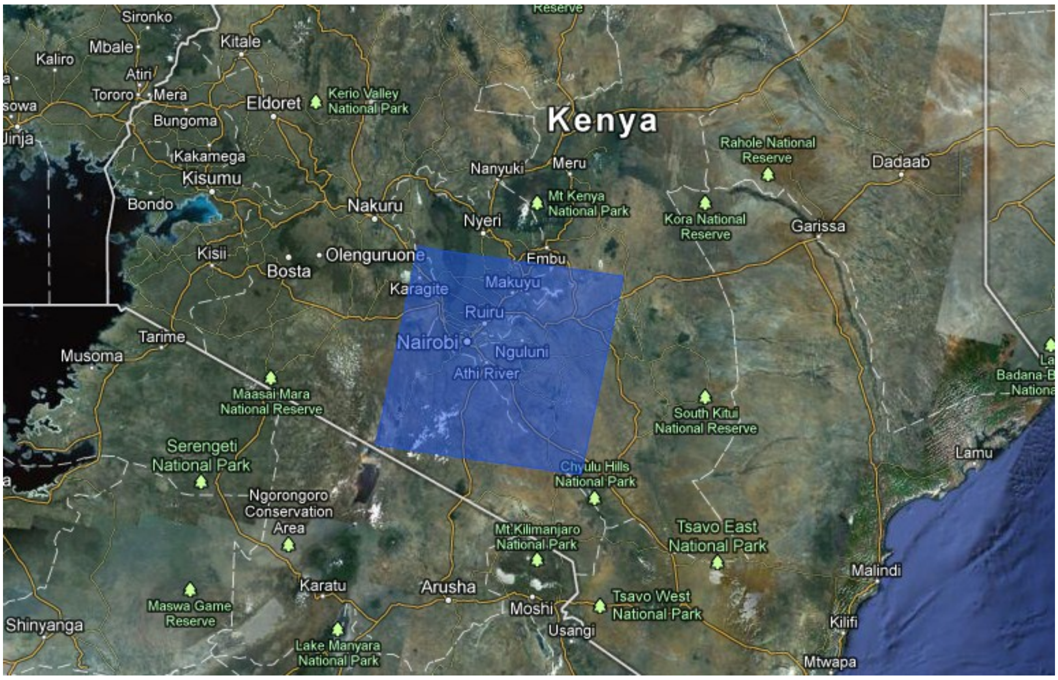
Images were sought for three major periods of water scarcity in the study area; 2005-6, 2008-9, and late 2010-2012. The droughts of 2005-6 and 2008-9 were both severe (Johnson and Wambile, 2011) and 2011 was recorded as one of the driest in 60 years after three consecutive seasons of poor rains (FEWSNET, 2011). Severe water scarcity continued into 2012. Information about weather conditions at the time that satellite images were taken was gathered from the Famine Early Warning Weather

Hazard Reports archives (FEWSNET, 2012); these reports are at a district and regional level. Detailed and accurate local historical information, such as precipitation data, was not available at the study site level, since records for the closest weather stations did not include data for the sample period (FAO, 2005; FAO, 2007).

Images from the Landsat 5 and Landsat 7 missions were selected for their high resolution (30m x 30m), and low cloud cover (less than 10%). Landsat 5 images can be used interchangeably with Landsat 7 images (Vogelmann, 2001). High resolution images are necessary to capture differences in vegetation at the relatively small scale of a sand dam, since their zone of influence is typically a small strip of 50-100m wide (and up to 500m), and 200-300m long (and up to 2km) either side of the river (Maddrell, 2012). Images were sourced from the United States Geological Survey sites; Earth Explorer and GLOVIS (United States Geological Survey a, b). Data from these sites is freely available.

The area covered by the set of satellite images selected is shown in figure 14 below. This swath (Path 168, Row 061) completely covers the study area.

Figure 14: Area covered by the satellite images used in this study (Landsat 5 and 7 Path 168, Row 061)

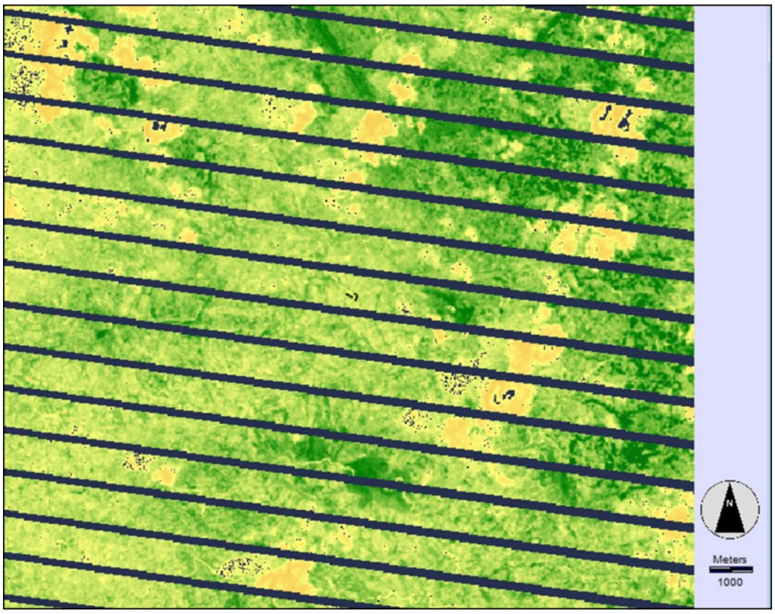


Source: United States Geological Survey, 2012a

Issues with Landsat 7 images

Since 2003, Landsat 7 images have contained ‘stripes’ of missing data due to a known error with the scan line corrector. The scan line corrector ensures images are aligned parallel to each other, since the satellite moves around the earth in parallel lines, or rows. However, with the error images are instead aligned in a ‘zig-zag’ or ‘stripe’ pattern, resulting in some areas that are imaged twice and others that are not imaged at all. The net effect is that approximately 22% of the data in a Landsat 7 scene is missing (Chen, et al., 2011; United States Geological Survey, 2012c, d). Figure 15 below shows part of an NDVI image of the study area derived from a Landsat 7 satellite image (path 168, row 061, taken: 12/06/2012). The effect of the SLC error is shown in by the black ‘stripes’, which do not contain any data. Although the impact of missing data can be mitigated for in processing stages, corrections were time consuming. Additionally, sample sites and controls that were completely obscured by the stripes were discarded and new ones chosen.

Figure 15: Representative example of ‘stripes’ of missing data at landscape level at study site*



**Note – the small rectangles at the centre of the image show the outline of one of the study sites*

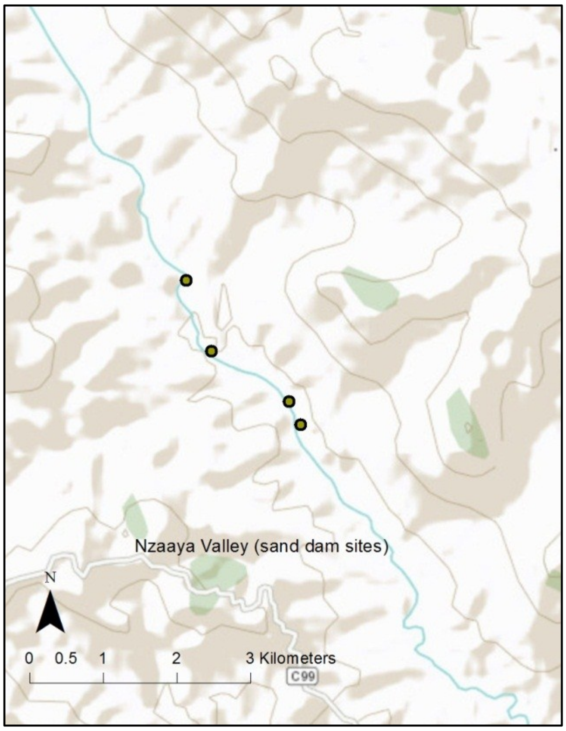
Although the Landsat 5 and 7 missions have a return cycle of 16 days, images are not freely available to the public for every pass. This combined with the missing data due to the SLC error limited the images available for selection in this study.

Selection of sand dam sites

Choice of sand dam sites was guided by availability of information from local experts about their location, when they were built and how well they had been maintained. It was important that the dams were mature enough to have harvested rainfall in the study period, thus further confirmation was sought that that the dams were at least filled with water at the time in the periods of water scarcity studied. An additional pre-requisite was that land use changes had not affected the performance of sand dam sites (ASDF, 2012; UDO, 2012). Availability of suitable control sites was also required.

Given these criteria four dams were identified for selection in the Nzaaya Valley. Figure 16 below shows sand dam sites overlaid on a topographical basemap of the area (ESRI et al.b, 2012).

Figure 16: Sand dams sites, Nzaaya Valley, Makueni, Kenya

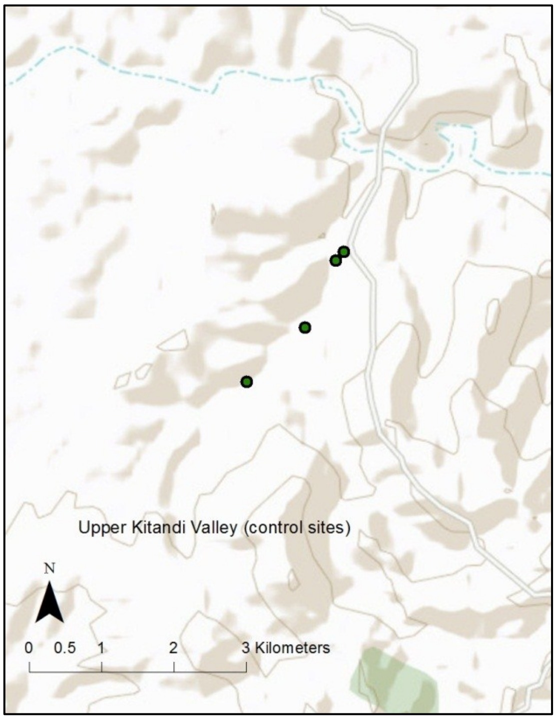


Selection of control sites

Control sites were placed in a different valley to samples in order to control for the impacts of other sand dams as described by Quilis et al. (2009), since additional sand dams have been built in the Nzaaya Valley.

The control valley was selected for its similar conditions to the Nzaaya Valley, including a dry sub humid climatic zone (FAO, 2005) and gentle slopes (1-3% gradient). Soil types for both valleys are given as upland soils that are "well drained, moderately deep to very deep, dark reddish brown to dark yellowish brown, friable to friable to firm, sandy clay to clay; in many places with a topsoil of loamy sand to sandy loam" (Jaetzold et al., 2006, p.388). Both valleys have the same agro-climatic zone suitable for growing the same crops including maize, sorghum, beans, tomatoes, onions and sisal (Jaetzold et al., 2006). Local knowledge was sought to confirm that a similar amount of sand had accumulated in the riverbed as controls, and that there were comparable land use patterns such as a lack of other sand dams or sand harvesting (ASDF, 2012). Four sites were identified for selection in the upper Kitandi valley. Figure 17 below shows control sites overlaid on a topographical basemap of the area (ESRI et al.,b, 2012).

Figure 17: Control sites, upper Kitandi Valley, Makueni, Kenya

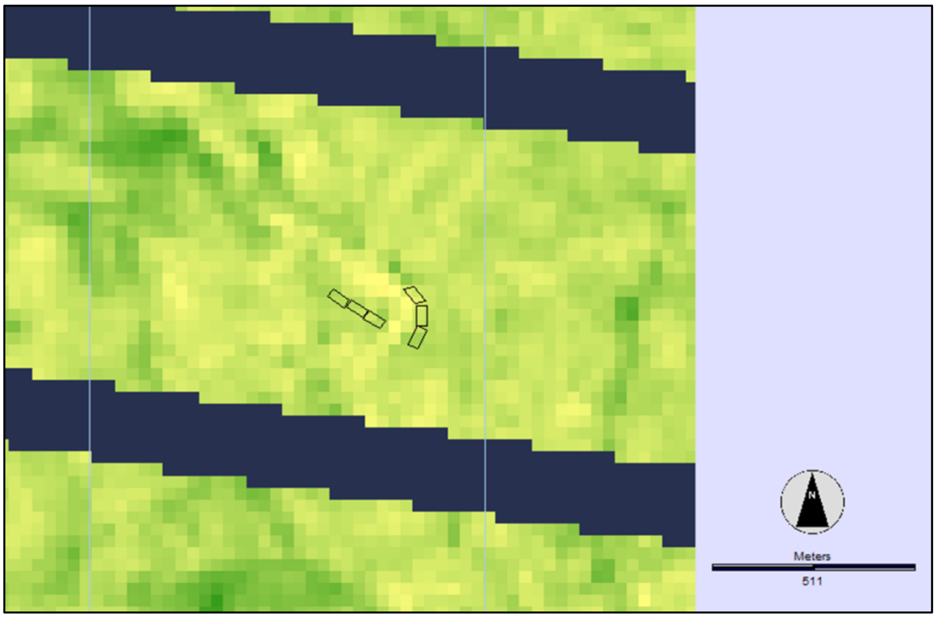


The criteria of similar land use and the effect of missing data due to the SLC error in Landsat 7 images limited the choice of control valleys. However, with the exception of altitude, all criteria are matched. The control valley is on average 150-200 m higher, but this was not expected to affect consistency due to the similarity of other characteristics including suitable conditions for cultivation of the same crops in both valleys (Jaetzold et al., 2006).

Selection of the buffer areas (for NDVI measurement)

The zone of influence of a sand dam, or buffer zone around a sand dam, is anecdotally up to a maximum of 2km upstream of the dam and 500m each side of the river (Maddrell, 2012). However, much of this area is cultivated so in order to control for cropping, which could skew results, only the area adjacent to the riverbed (25m width) was sampled since this area is generally left un-cropped (Neal, 2012). In order to isolate the buffer zones, the sandy riverbed was also excluded since it has a different reflectance value to vegetation. This was achieved by breaking each sample and control buffer zone into smaller parcels (50m in length and 25m in width); these parcels are referred to as 'buffers' in this study. The small size of the buffers also meant that the impact of clouds, shadows, or missing data from the Landsat 7 error could be minimised since it would affect only a portion of the site rather than all of it, and could easily be corrected (see the pre-processing section for detail). Additionally, only the first 150m distance in length was sampled since that is where the effects of the dam are clearly observable and is a manageable unit for analysis. The buffers were created in ArcMap and placed lengthwise either side of the riverbed for both sand dam and control sites. Figure 18 below demonstrates how the buffers were overlaid on an NDVI image, derived from a Landsat 7 satellite image (path 168, row 061, taken: 12/06/2012).

Figure 18: Example of placement of buffers overlaid on an NDVI image



Final data selection

Finally, images were overlaid with sample dams, controls and buffers in ArcMap for visual inspection to gauge and filter out the impact of clouds, shadows and missing L7 data. Where sample sites or controls were completely obscured by clouds, shadows or missing data, images were deselected. The images listed in table 5 below are the final selection; they are named by the date they were taken. In total there are 13 images which give 52 data points for samples (from four sites) and 52 for controls (from four sites).

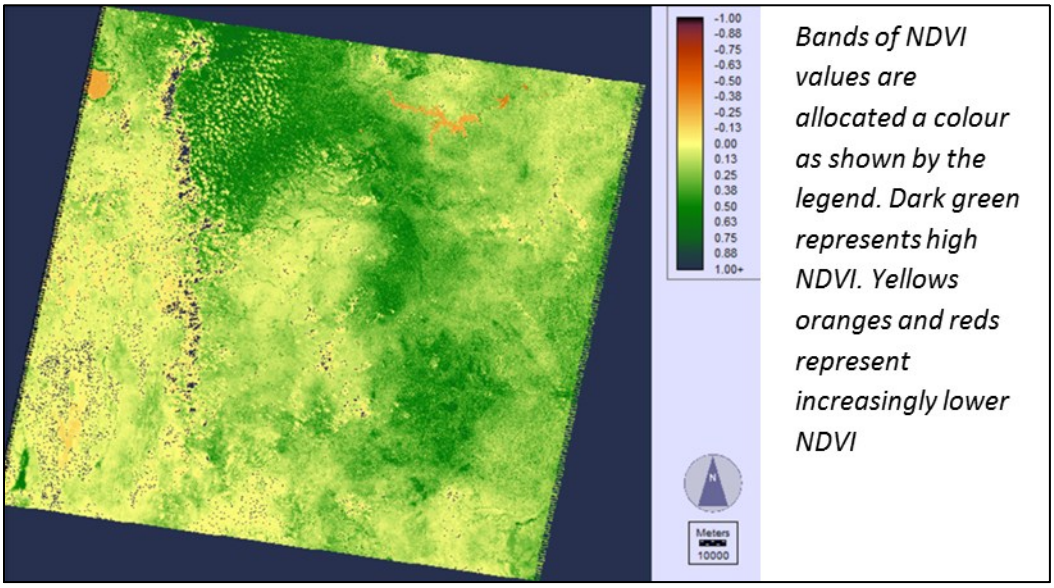
Table 5: Images selected for this study grouped by period of drought

2005-6	2008-9	2010-12
20050101	20080906	20101030
20050218	20090112	20101217
20051016	20090925	20101225
20060221		20110110
20061003		20120206

Image pre- processing

Image processing was necessary to align images to the same reference system (UTM37N) and determine NDVI values. All images were imported into IDRISI and geo-corrected so that rows and columns aligned across the image set. NDVI values were then determined by analysing Bands 3 and 4 in IDRISI to produce a series of NDVI images. Figure 19 below shows a representative sample of an NDVI image created for the study area, derived from a Landsat 5 satellite image

Figure 19: Example of an NDVI image for study area



NDVI values that returned a value of ‘0’ represented ‘stripes’ of missing data (United States Geological Survey, 2012c). Values of ‘1’ generally represent clouds. Values of ‘1‘ or ‘0’ were re-classed to ‘100’ and ‘200’ respectively, so that they could be easily identified in later analysis and corrected. This approach was chosen over more commonly used techniques where a mask image is created to exclude all missing values (United States Geological Survey, 2012c) since the study sites were so small (typically 2-3 pixels) that they would be obscured and no meaningful data would be available for study. Images were bundled together in a time series file for processing.

The buffers that had been created in ArcMap shapefiles were imported into IDRISI and converted to the same UTM37N map projection as the NDVI images, for processing.

Processing

Buffer layers were overlaid with the NDVI time series images in IDRISI and a PROFILE analysis was carried out. NDVI values were extracted for each buffer over the whole image set to create a temporal NDVI profile.

Each value was manually inspected for data integrity. Missing data, due to the SLC error and cloud cover, was easily identified due to the reclassification technique described above. A number of approaches were considered to correct for this missing data including:

1. Exclude all missing data and clouds – this was rejected since it made up around 20-25% of the data and would reduce the sample size to a point where statistical validity was compromised;
2. Interpolate NDVI values from other bands – this was not possible since the SLC error affected all bands;
3. Interpolate missing NDVI values from their nearest neighbouring pixels (Chen et al., 2011; Zhu et al., 2012). Again because study sites were so small (typically 2-3 pixels) this would have negatively affected integrity and resulted in no meaningful data.
4. A variation of this third approach was derived and selected, whereby:
    - Buffers that fell entirely under the stripes of missing data, clouds or shadows were given the average value of buffers at the same site (via manual calculation in spreadsheets);
    - Buffers that fell partially under stripes of missing data, clouds or shadows were assessed to find which pixels formed 70% of the buffer, and then the values of the pixels were averaged. Note, this is the same method utilised by the IDRISI profile tool so values returned were consistent.

The approach selected (no. 4 above) was chosen because it was found to be the most accurate way to correct for missing data given the small size of sand dam sites.

Analysis

Data was aggregated up from the individual buffers to the study site level and prepared for statistical analysis in the statistics package SPSS (Statistical Package for the Social Sciences). Tests for normality, including Levene's test, Kolmogrov-Smirnov and Shapiro-Wilk, indicated that the data conformed to assumptions of homogeneity of variance; hence parametric tests could be run.

To understand if there was a difference in mean NDVI values between the two groups (sand dams and controls), analysis of variance (ANOVA) tests were carried out. A basic ANOVA test is equivalent to a t-test, but because the same study sites were sampled on multiple dates, multiple comparisons over time are required to avoid pseudoreplicaton. Pseudoreplication occurs when the measurements from samples are related, or not independent of each other. This typically occurs if measurements are taken from the same subject or in this case the same sand dam or control site, but at different periods of time (Hurlburt, 1984; Field, 2005). T-tests do not account for this lack of independence. Moreover, multiple t-tests are not well suited to this situation either, since they would result in inflated Type 1 error rates (Field, 2005). Pairwise comparisons, which are similar to t-tests but take account of the familywise error could also be used but they have less statistical power than ANOVA tests (Field, 2005).

A repeated-measures ANOVA test (rANOVA) was selected as the most appropriate for this analysis since it accounts for related measures (Field, 2005). The use of multivariate ANOVA test was not possible as the number of repeated measures was high in comparison to the number of sites. Since there were only two conditions in this study (sand dams and controls) the rANOVA was not subject to violation of the assumption of sphericity (Field, 2005). Since the main concern was the between-group effect (i.e., dams vs. controls), which is not impacted by this assumption, it was not of concern in this case. The rANOVA reduces the chance of unsystematic variability and has greater power to detect effects than t-tests. Moreover, generally fewer samples are required (Hurlbert, 1984; Field, 2005). The rANOVA treated sites as subjects, and sample date as the repeated measure.

When considering a single date which represented “extreme drought” conditions, a t-test was used to compare sand dam and control sites.

Preliminary investigation

Initial trials revealed that the Landsat images were not of sufficiently high resolution to define riverbed limits, so Bing and Google Earth images were used to accurately delineate target areas. The effects of sand dams are likely to be more pronounced upstream (Hoogmoed, 2007; Hut et al.,2008; Quilis et al., 2009), accordingly all samples and controls were placed upstream of dams (or in the case of controls, upstream of areas where dams could be built). The resultant sample design had six buffers upstream of the dam for each site, three each side of the river, extending 150m upstream.

The rANOVA and t-test were run and analysed. Results are given in the next section.

4. Results

This chapter lays out the results from analysis and describes the main patterns that can be drawn from them.

All samples

The overall treatment effect for all samples is a highly significant statistical difference between mean NDVI values at sand dam sites compared to controls ($F = 18.779$, $p= 0.005$). This means there is a less than 0.5% probability that the difference was found by chance (see Appendix 1.1.1 for detailed results).

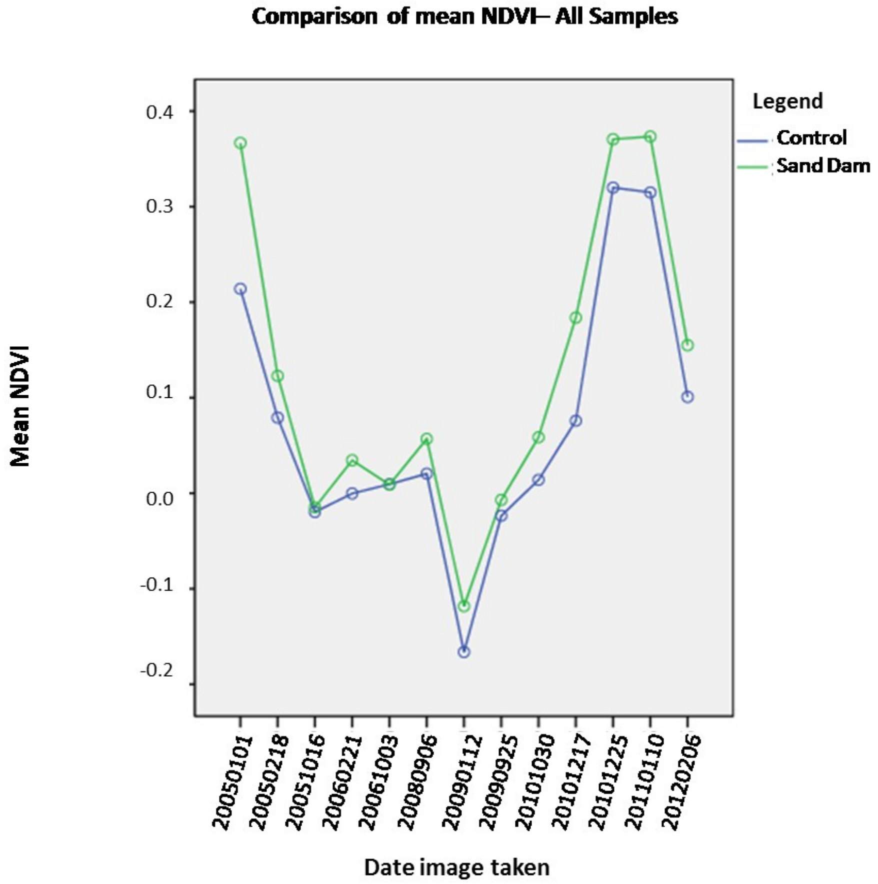
Table 6 gives descriptive statistics for all samples and shows that the mean NDVI for sand dam sites was 0.122, which represents a value consistent with vegetated surfaces. The value for control sites is 0.072 which represents bare or sparsely vegetated soils (Weier and Herring, 2012). The mean difference in mean NDVI between sand dams and controls was 0.05. The upper and lower bounds of the 95% confidence intervals for sand dams and controls do not overlap reflecting statistical significance even when allowing for 5% variability around the mean.

Table 6: Descriptive statistics for sand dam vs. control NDVIs - All Samples

Treatment	Mean NDVI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Sand Dams	.122	.008	.102	.142
Controls	.072	.008	.052	.092

Figure 20 below plots the difference of mean NDVI for each satellite image date and shows mean NDVI is higher for sand dams compared to controls across all 13 different dates sampled.

Figure 20: Comparison of mean NDVI for each date - All Samples



Response to variations in water scarcity

Differences in response of NDVI were found where variations in the degree of water scarcity occurred. Three conditions of water scarcity and related NDVI response were identified:

1. 'Drought 'conditions: In this case mean NDVI values were less than the threshold for vegetated surfaces (NDVI=0.1), but greater than zero. Most images fell under this category;
2. 'Extreme Drought' conditions: In this case mean NDVI values were consistently negative. One image fell under this category;
3. 'Relative Greening': In this case mean NDVI values were greater than 0.2. Historical reports for Makueni District by FEWSNET (2012) and the Kenya Food Security Steering Group (2012) suggest that 'showers' occurred around the dates the images in this category were taken within the overarching periods of regional drought. Although it is not conclusive, this study assumes that showers occurred over the study sites immediately before the images were

taken, resulting in the much higher NDVI values observed. Three images fell under this category.

Table 7 shows which images fell under each of the above categories. Note, they are named by the date that the images were taken.

Table 7: Images with NDVI results falling under the 'Drought', 'Extreme Drought', or 'Relative Greening' conditions

Drought	20050218, 20051016, 20060221, 20061003, 20080906, 20090925, 20101030, 20101217, 20120206
Extreme Drought	20090112
Relative Greening	20050101, 20101225, 20110110

'Drought' conditions

A significant difference between mean NDVI values at sand dam sites compared to controls was again observed during 'Drought' conditions (F = 8.766, p= 0.025), see Appendix 1.2.1 for detailed results.

Table 8 gives descriptive statistics for 'Drought' condition samples and shows that the mean NDVI for sand dam sites was 0.067, and the mean NDVI for control sites is 0.029. The mean difference between sand dams and controls was 0.038. Although the value at sand dam sites is nearly 2.5 times greater than controls, the mean NDVI value for sand dams (0 .067) is still less than the threshold of 0.1 for vegetated surfaces.

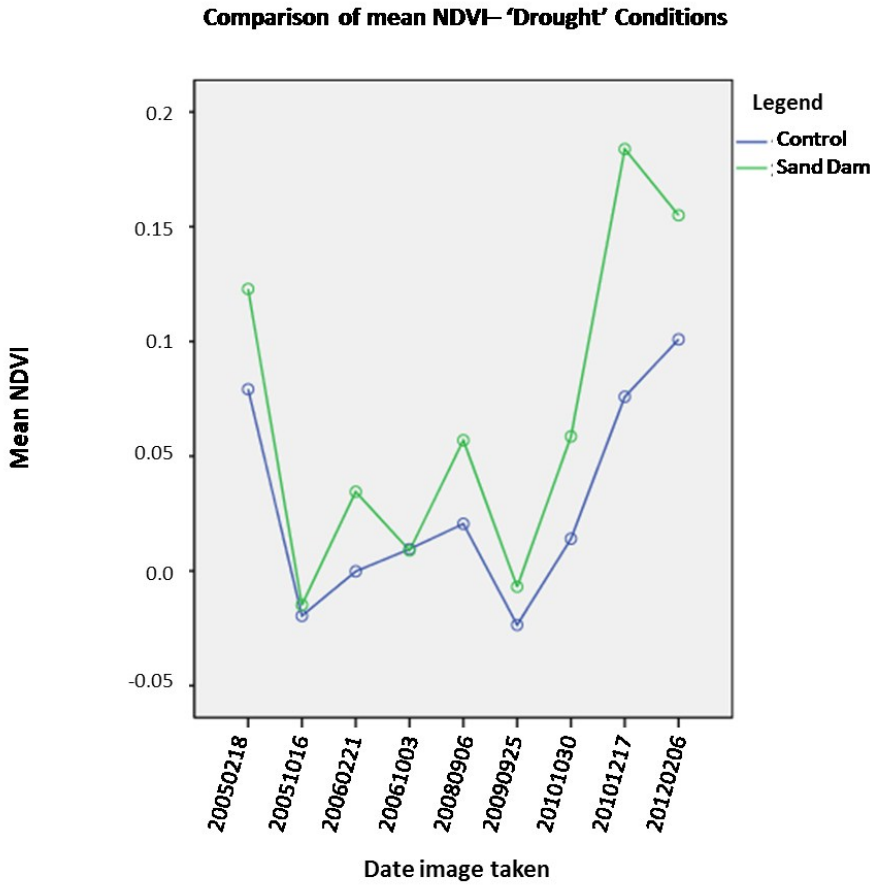
The upper and lower bounds of the confidence intervals for sand dams and controls only slightly overlap and statistical significance is still assured when allowing for 5% variability around the mean.

Table 8: Descriptive statistics for sand dam vs. control NDVIs - 'Drought' conditions

Treatment	Mean NDVI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Sand Dams	.067	.009	.044	.089
Controls	.029	.009	.006	.051

Figure 21 below plots the difference in estimated marginal mean NDVI for each satellite image under 'Drought' condition dates. The mean NDVI is higher for sand dams compared to controls across all nine different dates sampled.

Figure 21: Comparison of mean NDVI for each date – 'Drought' conditions



'Extreme drought' conditions

All NDVI values for this period were much lower compared to the results for the 'Drought' conditions. The values returned were consistently negative, whereas other conditions seldom returned negative values.

A t-test was carried out to determine the difference between sand dams and controls since only one image, or one measure, fell under this condition. In this 'Extreme Drought' condition vegetation at sand dam sites again had statistically significant higher NDVI values (P=0.016) than control sites (see Appendix 1.3.1 for detailed results). The mean difference between samples and controls was 0.048, or an improvement by roughly one quarter at sand dam sites. Table 9 shows the mean NDVI values for sand dam sites was -0.118, and for controls it was -0.166. These values typically represent rock and barren surfaces (Weier and Herring, 2012).

The upper and lower bounds of the confidence intervals for sand dams and controls only slightly overlap and statistical significance is still assured even when allowing for 5% variability around the mean.

Table 9: Descriptive statistics for sand dam vs. control NDVIs - 'Extreme Drought' conditions

Treatment	Mean NDVI	Std. Error Mean	95% Confidence Interval for Mean	
			Lower Bound	Upper Bound
Sand Dam	-.118	.011	-.154	-.082
Control	-.166	.009	-.195	-.137

'Relative Greening' – after light rains

NDVI values under conditions of "Relative Greening" were sometimes an order of magnitude higher for both sand dam sites and controls compared to 'Drought' and 'Extreme Drought' conditions. A highly significant difference between mean NDVI values at sand dam sites compared to controls was found during these 'Relative Greening' conditions (F = 38.780, p= 0.001). See Appendix 1.4.1 for detailed results.

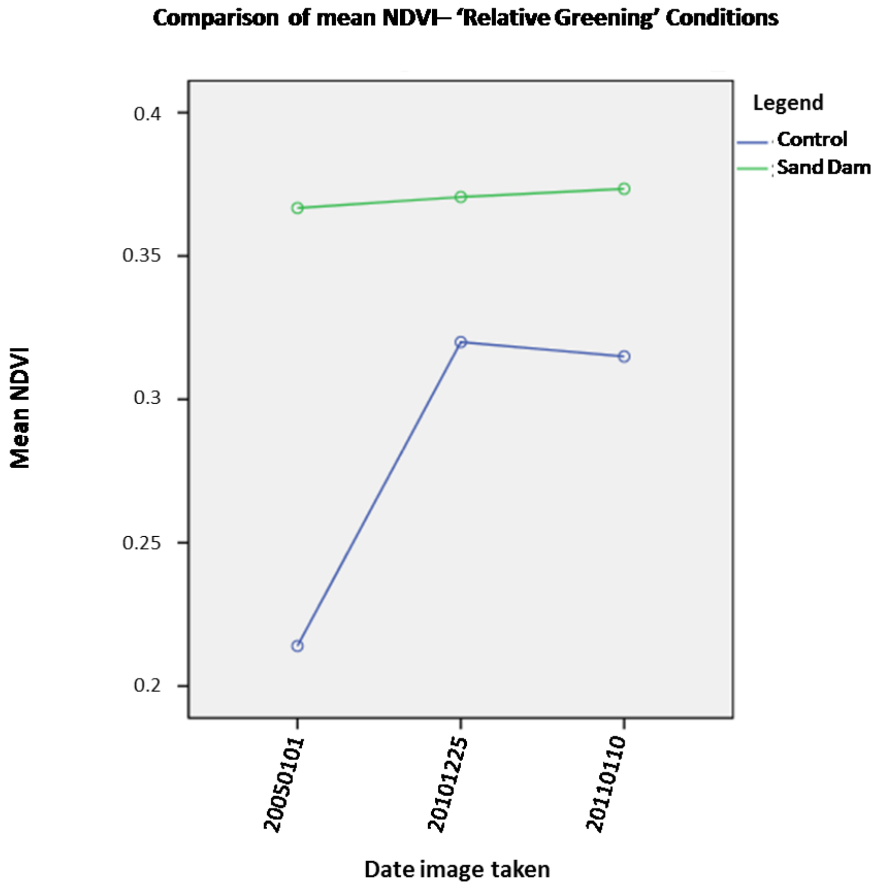
Table 11 shows the mean value for sand dam sites was 0.370 - typically representing healthy savannah or woodland vegetation, compared to 0.283 for controls - typically representing grass and shrubland (De Fries et al., 1995; De Fries et al., 1998). The mean difference was 0.087 which is nearly a whole 0.1 higher. 95% Confidence Intervals for sand dam and control sites do not overlap representing high reliability of results.

Table 10: Descriptive statistics for sand dam vs. control NDVIs - 'Relative Greening' conditions

Treatment	Mean NDVI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Sand Dam	.370	.010	.346	.394
Control	.283	.010	.259	.307

Figure 22 below plots the difference in estimated marginal mean NDVI for each satellite image under 'Relative Greening' condition dates. The mean NDVI is much higher for sand dams compared to controls across all three different dates sampled; moreover the sand dam NDVI values are consistently high compared to controls which are more variable.

Figure 22: Comparison of mean NDVI for each date - Relative Greening' conditions



5. Discussion

This chapter interprets results and discusses them in the in the wider context of the previous findings outlined in the literature review. It also provides a critique of the study, the problems that occurred and suggests improvements and future directions.

Interpretation of results

NDVI is a proxy for plant health, productivity, and biomass. A relative increase in NDVI can indicate an improved resilience to adverse conditions such as drought. The hypothesis that sand dams increase the adaptive capacity of drylands by increasing the resilience of vegetation through times of water scarcity is supported by the results of this study. Mean NDVI at sand dam sites is consistently, statistically and substantially higher than at control sites through periods of water scarcity.

When all samples were analysed together the difference between sand dam sites and controls was substantial. Sand dam sites maintained a mean NDVI consistently above the threshold for vegetated surfaces, whereas the mean NDVI for controls was below this - in the category of bare or sparsely vegetated surfaces. Importantly, this suggests that vegetation at sand dam sites is better able to withstand the shocks of drought disturbances.

Three findings were drawn out relating to different water scarcity conditions. The most substantial of these was that after showers occurred within a drought period, the 'Relative Greening' effect was more substantial at sand dam sites. Sand dam sites recovered to a mean NDVI of 0.37, which is higher than the average long term mean NDVI of 0.32 for the whole of the Kenyan Arid Lands region 2004 - 2009, including both drought and non-drought periods (Johnson and Wambile, 2011). Conversely, controls remained below this level. This meant sand dam sites had a positive difNDVI value, suggesting sand dam sites were elevated out of drought conditions, whereas control sites remained in drought conditions (Song et al., 2004). The mean difference between sand dam and controls for this case was nearly 0.1, which in this case typically represents the difference between a grassland and a savannah, or woodland biome (De Fries et al., 1995; De Fries et al., 1998). However, a greater spatial and temporal distribution of samples would be needed to be assured that NDVI is accurately mapped to biome type.

During 'Drought' and 'Extreme Drought' conditions, NDVI values at sand dam sites were consistently higher than controls, although they were still below the threshold for vegetated surfaces indicating they are affected by droughts but less so than sites without sand dams. This was evident even during the drought of 2008/2009 which was more severe and lasted longer than most (International Livestock Research Institute, 2010). The very low NDVI values for both sand dam and controls during this period are comparable to average values found by Anyamba and Tucker (2005), in a period of extreme drought across the Sahel 1983 to 1985.

The effects observed here are consistent with our understanding of groundwater flows around sand dams from previous research. Sand dams increase groundwater storage in river banks by 40% (Borst and De Haas 2006; Jansen 2007; Hoogmoed 2007; Hut et al., 2008), and groundwater is maintained throughout dry seasons and drought, increasing the length of time communities in south east Kenya have water reserves by 2.5 months (Borst and de Haas, 2006; Hut et al., 2008; Pauw 2008; Quilis et al., 2009).

The increased groundwater storage means more soil moisture is available to plants, this is reflected by mean NDVI values that are consistently and significantly higher at sand dam sites than control sites in both drought and extreme drought cases, and substantially higher over all cases. This feature of sand dams increases the resilience of agro-ecosystems by enabling vegetation to persist through drought disturbances. This could mean the difference between subsistence or surplus by ensuring communities have provisions and are less vulnerable to the next drought and so increasing their adaptive capacity.

Additionally, we know that the aquifer is recharged with the first few days of rains (Borst and de Haas, 2006; Hut et al., 2008; Quilis et al., 2009). This is reflected in the results for the 'Relative Greening' condition, where sand dam sites had above regional average mean NDVI values that elevated them out of drought conditions. This again increases resilience of agro- ecosystems by enabling them to recover more quickly from disturbance. Moreover, this feature of sand dams is highly useful given that climate change is expected to bring more variable rainfall, with more frequent and intense floods (Sörensen et al., 2008). Sand dams would enable dryland communities to take advantage of these flood events, therefore again contributing to increased adaptive capacity.

NDVI is related to biomass and therefore land cover classes, or biome types (Tucker et al., 1985; De Fries et al., 1995; De Fries et al., 1998). Consistently higher mean NDVI at sand dam sites supports the findings that sand dams increase the amount of vegetated land cover classes (Manzi and Kuria 2011). An increase in vegetated land cover types reduces vulnerability of exposure to both drought and floods, since land cover alters evaporation, runoff and ground water recharge, erosion and land degradation (Sahin and Hall, 1996; DeFries and Eshleman, 2004). Although greater replication of spatial and temporal samples is needed to accurately describe the impact of sand dams on biome types, these results are sufficiently robust that assumptions can be made about the direction of change and its application to Net Primary Productivity (NPP).

Application

When NDVI values are related to established estimates for NPP for different biome types, the NPP at sand dam sites increases considerably (Prince and Goward, 1995; De Fries, 1998; Zheng et al., 2003; Running et al., 2004; Zhao and Running, 2010). Figure 23 shows that presence of sand dams results in a different biome type for the 'All Samples' and 'Relative Greening' conditions. For 'All Samples' the increase in NDVI at sand dam sites reflects a difference between a biome comprising bare soils, or sparely vegetated soils at control sites, and grassland. For 'Relative Greening' conditions the increase in NDVI reflects the difference between grassland and savannah or woodland (Prince and Goward, 1995; Zheng et al., 2003; Running et al., 2004.

Figure 23: Increase in NPP due to the presence of sand dams, as related to biome types[9]

Case	***Biome type at control sites***		***Biome type at sand dam sites***		***Increase in NPP at sand dam sites***
'All Samples'	Bare soils and sparse vegetation[10] (151 gC m-2 yr-1*)	→	Grassland (204 gC m-2 yr-1)	=	+53 gC m-2 yr-1 (35%)
'Relative Greening'	Grassland (204 gC m-2 yr-1)	→	Savannah (300 gC m-2 yr-1) or Woodland (455 gC m-2 yr-1)	=	+ 96 gC m-2 yr-1 (47%), Or +251 gC m-2 yr-1 (123%)

**Grams of carbon per metre squared per year (gC m-2 yr-1)*

Source: Prince and Goward (1995); Zheng et al. (2003); Running et al. (2004).

[9] *Includes above and below ground NPP except for 'Bare soils and sparse vegetation'*
[10] *Adapted from Prince and Goward (1995), originally labelled as 'shrubs and bare ground'*

An increase in NDVI, and therefore NPP, reflects favourable growing conditions and an increase in biomass, which translates to an increase in potential yields and income for agro-ecosystems (Unganai and Kogan, 1998).

This is supported by findings that the average income of farmers increased in households with access to sand dams (Lasage, 2006; Pauw, 2008; Matuku, 2012). Moreover, food prices have been negatively related to NDVI anomalies in West Africa (Brown et al., 2006). In the case of 'Relative Greening', sand dams increase NPP to an average level that is suitable for most cultivation activities (398 gC m-2 yr-1; Zheng et al., 2003). This increases adaptive capacity by enhancing conditions for crops and enabling improved food security. However, this figure only represents average NPP for cultivated lands, and would not suit all crop types. Additionally, productivity under the increased $C0_2$ levels expected with climate change is uncertain, and figures may increase or decrease in climate change conditions (Fischlin et al., 2007).

Because NPP is the basis of the carbon cycle and affects the balance between sources and sinks (Running, 2004), a number of other applications can be drawn from the results found here such as potential for carbon sequestration, impact on biodiversity, and forecasting for agriculture (Pettorelli, et al. 2005). These topics also contribute to adaptive capacity but are outside the scope of this dissertation.

Critique of study

This study overcame problems of remoteness and limited information to produce sound and important information on the effectiveness of sand dams as a tool to increase resilience and reduce vulnerability to climate change. Despite technical challenges, four sand dam sites and four control sites were studied on 13 different occasions in a remote area of East Africa. Nonetheless, some minor limitations are considered below.

Design

Consistency between samples and control sites

An alternative explanation for the results is that the control valley may not have completely accounted for variances between the two valleys studied. However, both sample and control sites are in the same dry sub-humid climatic and agro- climatic zones, with the same soil type and are equally suited to grow the same crop types (FAO, 2005; Jaetzold, et al., 2006). Moreover both have the same gentle slope and land use, suggesting broad consistency between the two. Nonetheless, there may be site specific variations and the effect of the control valley being around 150m -200m higher is not fully understood. Without adequate rainfall records and field investigation into characteristics of each site and valley, differences cannot be fully accounted for.

Additionally, although the human impact of land use was understood to be similar in both valleys, a detailed assessment of the current and historical context, and land cover change could be useful to validate findings.

Alternatively, a longitudinal study of impacts of sand dam sites before and after they were built, with controls in the same valley could also address this point. However, a study area meeting these criteria could prove difficult since multiple sand dams are generally built in the same (and similar) valleys, thus suitable controls could be difficult to find.

Extent of buffers

Although results show that the buffers do reflect the zone of influence of sand dams, the extent of this zone is not fully understood. Whilst results demonstrate that sand dams influence the zone within a small distance of the sand dam, anecdotally this area is much larger. Research that investigated the full extent of the zone of influence would better inform the true impact on NDVI, provided the impacts of land use are controlled for. A study with several small blocks placed both upstream and downstream and extending into the valley sides could help answer this question.

Time period

The period studied looks specifically at times of water scarcity in the study area, however, examination of impacts through non-drought periods would further illuminate the impacts of sand dams. For example, the results of the period of 'Relative Greening' imply that NDVI and consequently NPP are much higher at sand dam sites than the regional average in times of relatively high water availability.

Additionally, examination of a much longer historical period with regular samples would better show the impacts of sand dams in the context of the climate cycles such as La Niña and El Niño. This would also shed light on how sand dams perform during a range of climate anomalies including the onset of drought, a stage that is not well understood (Rulinda, et al., 2012), as well as the impacts of lag between the onset of drought and vegetation senescence (Ji and Peters, 2003). Sampling of much older dams would be necessary to show the impact of sand dams in these contexts. Moreover, given that climate change is expected to bring greater variability the best temporal scale to sample is not clear.

Land cover

Although NDVI is a well-accepted and widely used vegetation index to ascertain biomass, it does not give visibility of changes in species composition or soil conditions. This is relevant because results cannot discern if an increase in NDVI is due to an increase in desirable or undesirable species – for example an aggressive weed species could exploit the favourable conditions created by sand dams. Similarly, NDVI cannot show the impacts of land use change, for example leaving crop land to fallow, nor an increase or loss in soil fertility. For this reason ground truthing to identify land cover classes, or biome types, could greatly increase the internal validity of the research design. Although this is obviously not possible to do for past periods, it could better inform the current situation, validate assumptions around biomass, and provide a baseline to monitor the impacts of sand dams in the future.

Vegetation Index

The accuracy of results could be refined by using the Soils Adjusted Vegetation Index (SAVI). This index has been created specifically for areas with a high amount of bare soils such as deserts and semi-arid areas (Pettorelli, et al., 2005). Ground truthing would be required to create spectral signatures specific to soils in the study area.

Socio-economic impacts

Validity of quantitative studies is greatly enhanced by verifying whether the same results are found using different methods such as qualitative research. Detailed mappings of the relation between the physical and socio-economic impacts of sand dams would help to provide this validity. An area of particular interest is the relation between the impacts of sand dams on NDVI, NPP, yield and income. Although a small number of studies exist on socio-economic impact of sand dams, none are known to address yield as related to income specifically. A study or collaboration to combine all of these factors would provide strong evidence of the economic impact of sand dams, and contribution to building adaptive capacity.

Availability of data

Sand dams

The scope of sand dam selection was limited by availability of good examples of sand dams and their records. Anecdotally, more mature dams have a greater impact on the surrounding environment. Whilst dams aged more than 30 years exist in the area, information about them was not possible to access within the time and resource constraints of this study. Nonetheless, although greater replication of samples is always desirable, the results from this study are suitably robust.

Weather records

Local observational records for weather in the sample valleys, such as precipitation, were not available for the period studied for the study area. However, variation in rainfall distribution between valleys in the study area is large and could potentially make a difference to results. Internal validity of the results could be improved by use of automatic weather stations or at least automatic rain gauges.

Satellite imagery

The irregularity of temporal distribution of Landsat 5 and 7 satellite images available for this study, and the impact of missing data due to the Landsat 7 SLC error meant that a comprehensive temporal data set could not be analysed. This also prevented selection of older sand dams for which information was available, since suitable controls were completely obscured by the 'stripes' of missing data.

Image processing methods

The manual approach to image processing used in this study to resolve the Landsat 7 SLC error provided the most accurate results possible, however, this approach is too time consuming to feasibly scale up to a larger study. Future work should focus on finding a way to at least partially automate image processing.

Future directions

Validation of findings through ground truthing of land cover classes is a key area for further research. A longitudinal assessment of impacts before and after sand dams were built, in the same valley, with controls would further support findings. A long term monitoring programme that combined these factors would provide valuable insight into the performance of sand dams in a variety of climate change scenarios, including drought and non-drought periods. Moreover, a new high resolution Landsat satellite is due to be launched in 2013, thus images without the SLC error will be available from that point forward.

Specific research mapping the impact of sand dams on NDVI, NPP, yields and income would provide a strong case for the cost benefits of sand dams and their contribution to building adaptive capacity. Such a study could benefit from expertise from the social sciences.

By increasing biomass and altering biome types, sand dams have the potential to increase the amount of carbon sequestered in dryland carbon sinks. Although this relates more to climate change mitigation than adaption it would be an interesting area to explore since it could potentially provide a case for sand dams as a climate change mitigation tool.

6. Conclusions

I have shown that the aims and objectives of this study have been met. The mean NDVI of vegetation at sand dam sites is consistently, statistically and substantially higher compared to non-sand dam sites through periods of water scarcity across all samples. Moreover, sand dams enable vegetation to recover more quickly in times of relative water availability within overarching drought periods.

The results were applied to find how sand dams affected biome type and consequently NPP. Sand dam sites were found to have mean NDVI values that consistently related to vegetated or very healthy biomes whereas controls did not. Consequently NPP was consistently higher at sand dam than control sites.

These findings support the hypothesis that sand dams increase the adaptive capacity of drylands by increasing the resilience of vegetation through times of water scarcity. Moreover, the findings are supported by the literature on groundwater flows and storage around sand dams, as well as impacts on land cover and socio-economic indicators.

It follows that the enhanced resilience increases the adaptive capacity of drylands agro-ecosystems to climate change, and that this technology is highly appropriate as an adaptation response to climate change in drylands.

The contribution of this study to the body of knowledge on sand dams is their impact on NDVI, which is not known to have been studied previously. NDVI is correlated to NPP which is a central component of the carbon cycle, and can also be related to crop yield and indirectly to other socio-economic indicators. This study contributes some insight into the effect of sand dams on NPP and is also the first to compare impacts of sand dams with control sites - thus controlling for regional climate influences. Given the relatively easy access to satellite image data, this study has the potential to act as a baseline for long term monitoring of sand dam impacts. Additionally it strengthens the case for the benefits of building sand dams in drylands as an adaptation response to climate change.

The results presented here could be strengthened by more detailed information on study sites, much of which could be obtained by detailed field research and complemented by longitudinal analysis.

Future research should seek to extend the scope and data sources such as including data from detailed field studies. Research over a longer time scale, including non-drought periods, would enhance understanding about the impact of sand dams in the context of climate cycles.

Additional future directions should include investigation into the impacts of sand dams on land cover classes, NPP as related to yield and income in collaboration with social science, and carbon sequestration.

vi. References

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vii. Appendices

Appendix 1 Results

All Samples

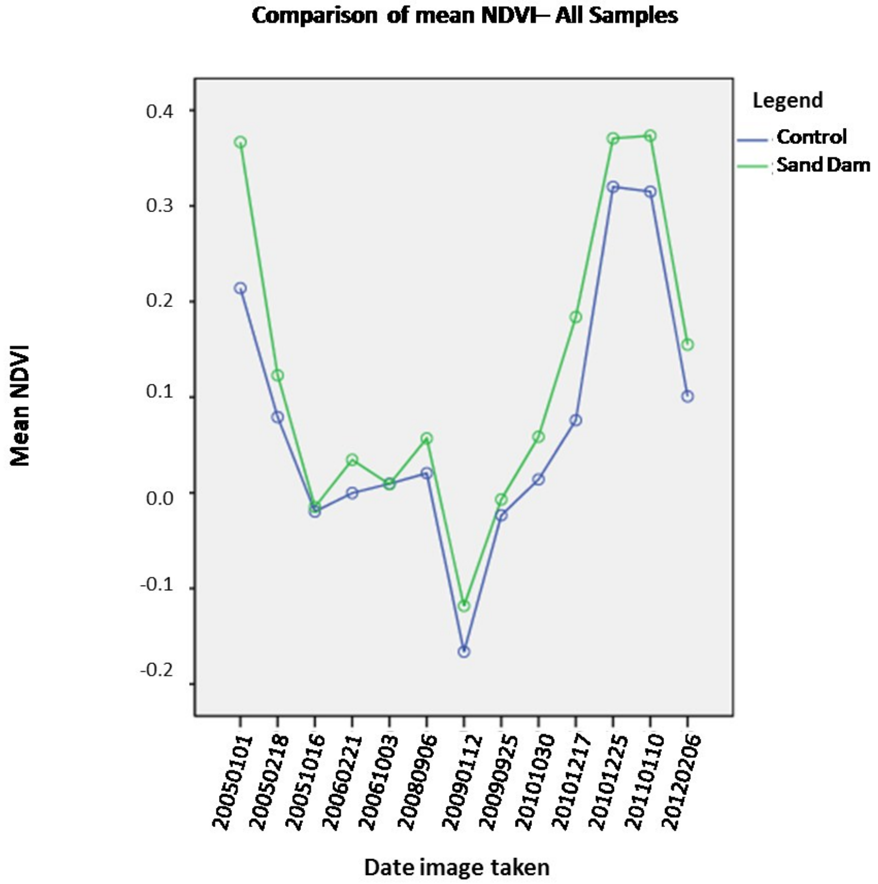
1.1.1 Results from Repeated Measures ANOVA (between subjects) - All Samples

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.985	1	.985	283.092	.000
Treatment	.065	1	.065	18.779	.005
Error	.021	6	.003		

1.1.2 Descriptive statistics for sand dam vs. control NDVIs- All Samples

Treatment	**Mean NDVI**	**Std. Error**	**95% Confidence Interval**	
			Lower Bound	**Upper Bound**
Sand Dams	.122	.008	.102	.142
Controls	.072	.008	.052	.092

1.1.3 Comparison of mean NDVI for each date – All Samples



'Drought' Conditions

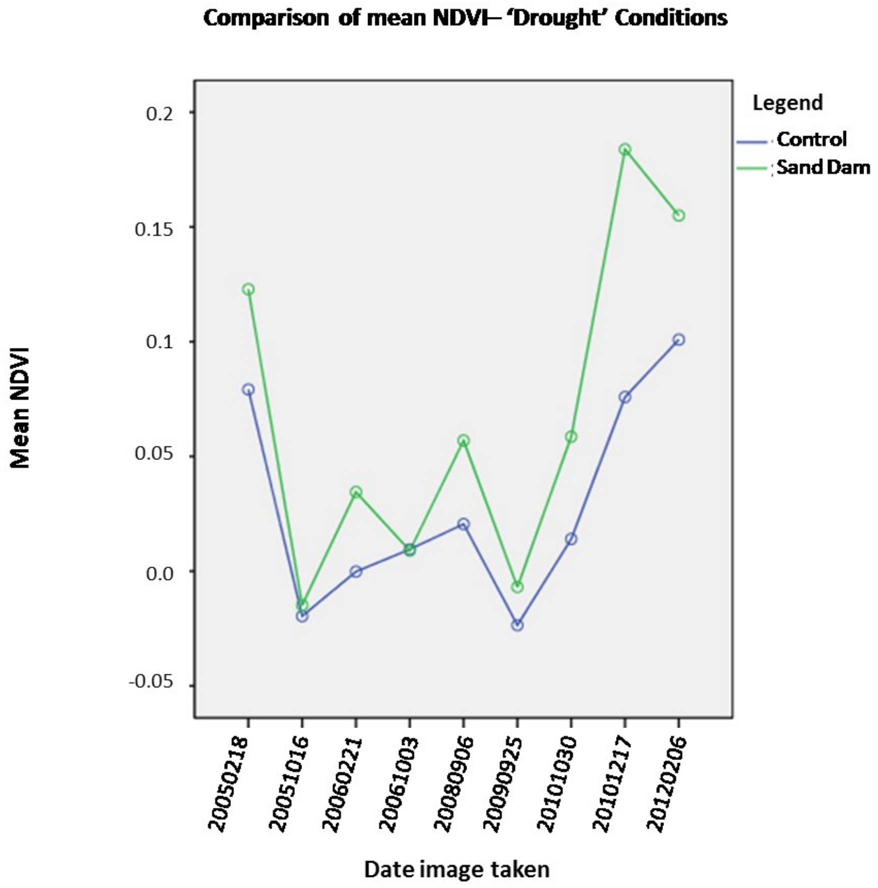
1.2.1 Results from Repeated Measures ANOVA (between subjects) - 'Drought' conditions

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.163	1	.163	54.838	.000
Treatment	.026	1	.026	8.766	.025
Error	.018	6	.003		

1.2.2 Descriptive statistics for sand dam vs. control NDVIs - 'Drought' conditions

Treatment	Mean NDVI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Sand Dams	.067	.009	.044	.089
Controls	.029	.009	.006	.051

1.2.3 Comparison of mean NDVI for each date-'Drought' conditions



'Extreme Drought' Conditions

1.3.1: Descriptive statistics for sand dam vs. control NDVIs – 'Extreme Drought' conditions

Condition	Mean NDVI	Std. Error Mean	95% Confidence Interval for Mean	
			Lower Bound	Upper Bound
Sand Dam	-.1182508295	.01126609173	-.1541045615	-.0823970975
Control	-.1661836597	.00911577936	-.1951941381	-.1371731814

1.3.2 Independent Samples t-test – 'Extreme Drought' conditions

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference NDVI	Std. Error Difference	95% Confidence Interval of the Difference: Lower	95% Confidence Interval of the Difference: Upper
Equal var. assumed	.186	.682	3.308	6	.016	.047932830	.014492144	.012471829	.083393830

'Relative Greening' conditions

1.4.1 Results from Repeated Measures ANOVA (between subjects) – 'Relative Greening' conditions

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	2.560	1	2.560	2172.723	.000
Treatment	.046	1	.046	38.780	.001
Error	.007	6	.001		

1.4.2 Descriptive statistics for sand dam vs. control NDVIs - Relative Greening' conditions

Treatment	Mean NDVI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Sand Dam	.370	.010	.346	.394
Control	.283	.010	.259	.307

1.4.3 Comparison of mean NDVI for each date- Relative Greening' conditions