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ORIGINAL ARTICLE

Back to the drawing board: assessing siting guidelines for sand dams in Kenya

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Abstract

Sand dams have become popular in many parts of the arid world as a relatively cheap and effective water harvesting technology. Kenya is one of the countries with the highest number of such dams, with semi-arid Kitui County having become a major hub in recent decades. These sand dams are used for water storage in the beds of Kitui's seasonal rivers. The water is used for households and small-scale economic activities. Generally, sand dams are evaluated as very successful, but this paper shows that such success is not guaranteed. Field research conducted in Kitui County in October 2016 suggests that from 116 sand dams surveyed, about half did not have any water during the time of the assessment. This study assesses how various environmental factors affect sand dams' ability to supply water for community use during dry periods in Tiva River catchment in Kitui County. Most of the assessed environmental factors did not show consistent patterns to draw inferences on how they affect sand dams' ability to supply water, with the exception of rainfall amount, water indicating vegetation percentage of clay in a soil and stream orders. More overarching factors like agro-ecological zones and stream order do show a pattern of influence on dams' performance. These results have global significance due to the widespread use or plans to use of sand dams worldwide. There is a clear need to build a better understanding of sand dams performance to define more reliable sand dams' site identification criteria.

Keywords Water use · Asals · Sand dams · Siting · Environmental factors

Abbreviations

AEZ	Agro-ecological zones
ASAL	Arid and semiarid lands
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GIS	Geographic information system
GPS	Global positioning system
HH	Household
IIASA	International Institute for Applied Systems Analysis
LM	Lower midlands
LU	Livestock unit
NGO	Non-Governmental Organizations
RCMRD	Regional Centre for Mapping of Resources for Development
SD	Sand dam
std	Standard Deviation
SPSS	Statistical Package for the Social Sciences
TWI	Topographic Wetness Index
UM	Upper midland
USA	United States of America
USD	United States Dollar
WHO	World Health Organization

Introduction

Arid and semiarid lands (ASALs) makeup 40% of the global land area and are occupied by 2.3 billion people, including 74% of the world's poorest (Mortimore et al. 2009). Limited access to water is to blame for many problems and disasters associated with ASALs. Poor rainfall characteristics result in poor livelihoods. In Kitui, Kenya, for example, recurrent crop failure affects access to food and incomes at least once every five seasons (Omoyo et al. 2015). In most other seasons, crops suffer suppressed growth due to less than adequate rains, but also because unreliable and unpredictable

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rainfall hinders investment in inputs for farming. This has led to a high poverty index of 63.5% in Kitui County against the national average of 47.2% (KCRA 2012).

As many others in ASALS, Kitui's inhabitants spend much of their time searching for water (Thomas 2000). Water sources in Kitui County include boreholes, shallow wells, earth dams, roof rainwater harvesting, seasonal rivers and sand dams. Boreholes are expensive to develop requiring support from the county government or donors. Furthermore, Kitui's boreholes often run dry after (Ngigi 2003) sometime due to limited aquifer recharge (Mburu 1989). A high number of boreholes in Kitui County have brackish water due to mineral composition of the parent rocks, especially those to the south of the county (Munyao et al. 2004). Shallow wells are not reliable either. They run dry as the drought intensity increases due to the receding water table. Small size earth dams are unsuitable as water sources due to the very high potential evaporation rates of between 1800–2400 mm per year (CGK 2014). Larger earth dams are expensive and generally all earth dams require regular desilting which is expensive. Roof rainwater harvesting systems are expensive and are practiced by only a few people who can afford them.

As such, many of Kitui's potential water sources are known to have problems, but so far the general opinion appears to be that sand dams (also known as sand-storage dams), built to increase water access from sandy seasonal rivers, are generally highly successful and a major technology to be implemented elsewhere (Thomas 2000; Lasage 2008; Quilis et al. 2009; Stern and Stern 2011). Storing water in sand dams has advantages compared to conventional dams. For example, sand dams reduce water evaporation substantially and do not result in breaching that could cause catastrophic accidents (Mansell and Hussey 2005). Beyond 60 cm below the sand level, evaporation becomes negligible (Wheater and Al-Weshah 2002; Diettrich, 2002; Sivils and Brock, 1981; Stern and Stern, 2011; Ertsen and Hut 2009). They minimize water contamination through livestock and wildlife droppings and human use (Nissen-Petersen, 2000). They do not result in breeding of mosquitoes (Nissen-Petersen 2006) and do not take up valuable land (Ertsen et al. 2005).

Typically, to guarantee success, sand dam sites are selected with certain criteria, that are considered to contribute to sand dams' ability to increase water supply from a riverbed. This paper explores whether existing criteria to decide where to locate the dams are adequate guides to ensure the sand dams provide water for community use during drought periods as evidenced by the presence of water during the period of the assessment as well as community interviews on when they usually stopped obtaining water from the sand dams. The paper also assesses whether reliance on such guidelines should be revised or not. Factors that were assessed include; soil, rainfall amount, topography, geology, presence of sub-surface water on a section of the riverbed for about a month after it got depleted in other sections and water indicating vegetation. This paper explores these environmental factors and their complexity as often they are dynamic and unpredictable. The factors were assessed individually to identify patterns that could be attributed to each. Assessing the concept of agro-ecological zones (AEZs) allowed considering possible interactions of these factors (Sombroek et al. 1982) and their combined influence in determining improved access to water from sand dams. An additional factor of stream order as proposed by (Strahler 1957) was also included in the assessment.

This study looks into the past to ascertain whether the forecasting of these criteria in Tiva catchment in Kitui County was accurate. Sand dams have indeed been successful in Kitui, in terms of increased access to water (Mansell and Hussey 2005), higher incomes (Lasage 2008; Excellent Development 2015), vegetation rejuvenation (Manzi and Kuria 2011), recharging groundwater (Thomas 2000), and in some cases rejuvenated streams (Ngigi 2003). Our paper suggests, however, that any unilateral success of sand dams may not be found. Even when constructed on locations that meet all the recommended environmental factors, many sand dams constructed along Tiva catchment in Kitui's County failed to provide water for community use as expected. We suggest that using sand dams to increase water access should be approached with more caution than has been the case in the past. Our findings are important for the larger debate on water shortages faced by communities in the ASALs and consequent implementation of new technologies for improving water access.

The number of sand dams that exist in the world may not be known. Excellent Development quotes about 4000 globally (Excellent Development 2015) with about 50% constructed in South Eastern Kenya counties, but the method used to establish this number is not indicated. As such, it is very likely that South Eastern Kenya has the largest concentration of sand dams on the globe, all developed in the last 100 years (Excellent Development 2015), with the majority from 1990s onwards (De Trincheria et al. 2015). These impressive numbers notwithstanding, we argue that similar to many other water resources development efforts in arid and semi-arid regions, sand dams face sustainability challenges due to uninformed decisions that are not backed by locally acquired data (see Wheater and Al-Weshah 2002). Sand dams bring renewed hope to communities who may even consider expanding their resource base to improve their livelihoods. Consequently, the failure of these interventions to improve access to water in ASALs is a problem that needs to be addressed. Lack of water adversely affects access to other basic necessities resulting in (a danger of) chronic poverty (Republic of Kenya 2015; Ngigi 2003).

In the sections that follow, sand dams are introduced. Then the method used in this study is outlined in more detail, followed by results and their discussion. Since sand dams are relatively expensive to construct given the high poverty levels in Kitui (MOA 2014), the conclusions and recommendations guide on what precautionary measures to use to minimize wastage of resources when building sand dams. Generally, this paper suggests that sand dams' designers and stakeholders should go back to the drawing board as reliance on sand dams to provide water during the drought periods needs to be re-evaluated.

Factors for the successful performance of sand dams

As elsewhere, Kenya's ASALs (80% of its area) are fragile environments, characterized by little and erratic, often unreliable rainfall (Shisanya, et al,. 2011). Tiva River catchment in Kitui County is no exception to this. The area receives two rainfall seasons per year: the short and long rainy seasons, which occur in November–December and April–May, respectively, with two inter-seasonal drought periods. The rainy seasons suffer wide variations in rainfall amounts and distribution from year to year (Lasage 2008). Rainfall failure in both seasons is common. The higher areas around Kitui town receive between 500 and 1050 mm (GOK 2013). Amounts decline to the South, with annual totals of less than 500 mm. With average temperatures relatively high at 24 °C, potential annual evapotranspiration in Kitui County is 1800–2000 mm (Kuria et al. 2012; Munyao et al. 2004). The inter-seasonal drought of June to October is more severe than the one from January to March during which the land receives occasional rain showers.

Apart from Tana and Athi, all other rivers in Kitui County are seasonal. Their riverbeds contain water for a limited period during and immediately following the rainy season. However, the seemingly dry riverbeds may carry subsurface water beneath the sand for prolonged periods of time after the rainy season. Subsurface flow rates can be substantial. A study in Zimbabwe that assessed flow rates in four sandy rivers estimated about 100m^3 per day (Mansell and Husseys 2005). It is this subsurface water that has been used by Kitui's communities since time immemorial. The local people scoop out the sand from the seemingly dry riverbeds to reach for water which lies beneath. As the drought period progresses, the water level in the sand bed drops, sometimes to a few meters deep (Mburu 1989), making access to water from the sandy riverbeds difficult and dangerous. Increasing access to water from these riverbeds is important as they are the most widely distributed water source in Kitui County.

To increase water volumes from these riverbeds, sand dams and to a lesser extent subsurface dams were mobilized. Sand dams are impermeable barriers (such as the reinforced masonry barrier in Fig. 1a and b) erected across the seasonal riverbeds to impound more sand and thus water (which

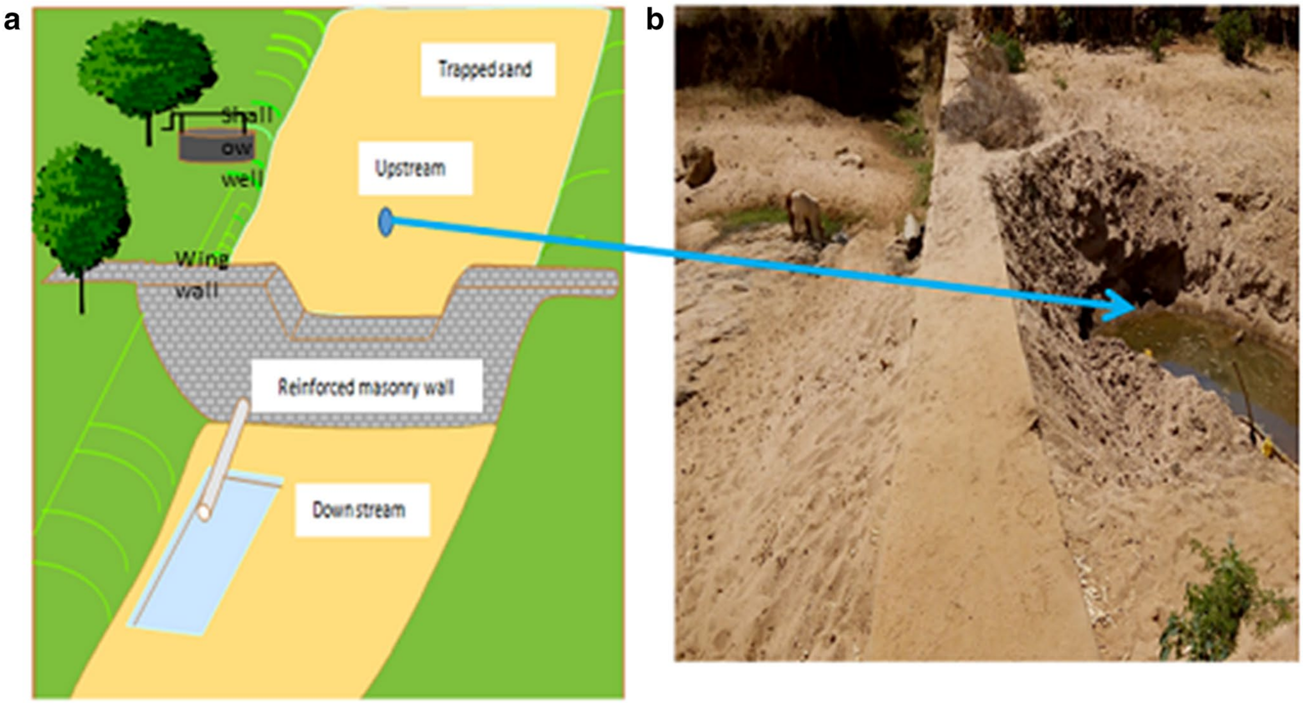

Fig. 1 **a** and **b** Sand-storage dam (Left image from (Ngugi 2002), right image was taken by Ngugi in October 2016)

comprises up to about 40% of the sand volume) (Mburu 1989; Thomas 2000). Unlike sand dams, sub-surface dams are similarly built but do not rise above the original sand level (Ngigi 2003). Sometimes sand dams are fitted with a shallow well on the upstream side from which water will be drawn. As a specific type of groundwater dam, sand dams have been a common feature in many arid parts of the world such as the Middle East, China, South Africa, Zimbabwe, Mozambique, India, Japan and United States of America (USA) (Diettrich 2002). In the USA, sand dams were used to provide water in the South Western regions before the extensive water-supply systems were installed. In 1973, a sand dam equipped with perforated metal pipes covered in gravel and sand provided water for livestock in underutilized South-Western rangelands (Sivils and Brock, 1981). Later, Bleich and Weaver (1983) proposed improvements in efficiency, dependability, simplicity as well as decreased installation and maintenance costs.

From the impressive number of dams in Kenya, not all these sand dams have resulted in increased access to water for local communities. Following the intensification of sand dams construction, several sand dams have been reported to have failed to supply water as expected (Olufisayo et al. 2010; De Trincheria et al. 2015; Nissen-Petersen 2006, 2011; Ertsen and Hut 2009). Nissen-Petersen (2006), a key stakeholder in sand dams' development, admitted that 9 out of 10 recently constructed dams were not functional in South Eastern Kenya although this study did not confirm it. Each sand dam costs an estimated United States Dollar (USD) 5000 (Ertsen and Hut 2009) to 10,000 (Excellent Development 2016), resulting in wastage of valuable resources when dams fail. Dam failures have been blamed on poor site identification, environmental degradation and poor construction procedures.

When defining those factors that must play a role towards increasing access to water from sand dams, developers and communities used logical reasoning. Their river networks contained only coarse sand, beneath which they found water whose quantity they sought to increase. They reasoned the catchment soil textural characteristic should be able to yield coarse sand and recommended those high in sand content. Gijsbertsen (2007) supported this reasoning, and studied suitable catchments as being those whose riverbeds were full of coarse sand. Nissen-Petersen (2013) recommended catchments with stones and rocky hills that were a source of coarse sand into the riverbed during rainfall storms. The storms also flushed away clay and silt particles further downstream leaving the coarse sand behind. Presence of rock outcrops implied there was more of it underneath which acted as an impermeable layer that held water in place. Developers needed the land to be sloping to aid the rainfall delivering the coarse sand and, therefore, realized flat and very gently sloping land should be avoided. Gijsbertsen (2007) showed indeed, very gentle slopes resulted in river beds with fine-textured sediments.

Developers also needed river banks that would not collapse and fill the sand dam with the soil of undesirable textural characteristics and avoid re-routing. Besides, it was on these riverbanks that the masonry walls would be anchored in a trench. It was found better to erect sand dams on sections of the riverbed that contained more subsurface water, as those sections were last to dry up. Riverbed sections that had water indicating vegetation were also favoured (Nissen-Petersen 2000). Thus, rainfall, soil, topography, lithology, riverbanks, water indicating vegetation, sections of the riverbed where sub-surface water lasted at least one month after it got depleted in other parts were all included in the site selection criteria for sand dams. Finally, developers recommended building sand dams across riverbeds that were less than 25 m wide (Nissen-Petersen 2006) as more was found to be too expensive relative to annual household incomes estimated at USD 600 (MOA 2014). To make sure silt and clay particles were not retained in the sand dam, it was recommended to raise the dam height in stages equivalent to the expected quantity of coarse sand.

Despite these clear indicators, finding suitable sites for constructing sand dams is not straightforward. Catchments may change. A catchment with adequate amounts of sand to fill a sand dam within 2 years could have lower yields after soil and water conservation measures like terracing land (Tiffen et al. 1994; Wang et al. 2013) or produce sediments of different texture (Ouyang and Bartholic 1997a, 1997b). Gully erosion – common in Kenya's ASALs – may result in sediments with undesirable textures (Nissen-Petersen 2011). A gentle slope may still yield more coarse sand than a steep slope in different catchments with similar soil and rainfall characteristics due to interactions between geology or human occupation. In general, as land use and land cover changes may affect textural characteristics of sediments getting into the sand dams, the current existence of coarse sand in a riverbed to determine whether a catchment yields adequate sand may be misleading. Even catchments with low quantities of sand will have managed to fill the riverbed with sand in longer periods.

The slope of the land may not be uniform and can vary greatly within the same catchment, which results in both erosion and deposition occurring concurrently (Alatorre et al. 2012). The slope of a catchment can be artificially modified through human activities (Tiffen et al. 1994). An impermeable rock or clay layer providing an impermeable base beneath the sand in a riverbed is not easy to identify, as its extent cannot be established without thorough and detailed geological assessment, which was the reason for Gijsbertsen (2007) to ignore this property of a site. The rock may be porous as well. Furthermore, as has been reported by Woodhouse (1991), tectonic movements can create faulting in geology causing impermeable rocks to leak, possibly resulting in sand dams losing their water altogether. Water indicating vegetation may no longer be at sites, as trees may have been cut down for timber, firewood and charcoal.

The rainfall amount adequate for water supply from sand dams is poorly defined as well. Adham et al. (2016) recommended regions with more than 200 mm. Mati et al. (2007) recommended rainfall/Evapotranspiration (ET) ratio (moisture index) of < 60% and presence of ephemeral rivers without defining a lower limit. Beimers et al (2001) mentioned a (high) range of 700–900 mm, as most ASALs receive less than 500 mm. Rainfall amount, intensity and distribution are highly dynamic in ASALs, which make recharging sand dams unpredictable as well. Spatial rainfall variability within the same catchment implies a dry section of a catchment could receive runoff from upstream, complicating defining minimum rainfall amounts for successful water supply from a dam. Rainfall amounts in ASALs seem to be declining, implying a reduction in runoff and sediments (Khisa et al. 2014; Wamari et al. 2012; Shisanya et al. 2011; FEWSNET 2010; Patricia 2010; Njiru 2009). Getting sites that meet all the listed conditions (Table 1) is difficult. Furthermore, the factors themselves are complex and dynamic. It is expected that existing sand dams, both successful and unsuccessful ones show complex configurations of characteristics, with their ability to supply water varying as much as these characteristics.

To have a grip on dam performance in relation to the factors, this research has assessed some of the stated environmental factors individually to identify their contribution to water access from sand dams. It explores a set of environmental characteristics that are considered to contribute to sand dams' ability to increase water supply from a riverbed. Jamali et al (2013, 2014) considered abiotic factors such as slope, geology and soil within GIS including Topographic Wetness Index (TWI) values and stratigraphic information to identify suitable sites for subsurface dams. Encouraging results were obtained in regions with humid climates and limited natural water storage capacities. Adham et al. (2016) confirmed the use of these factors in its review of 48 studies on siting of rainwater harvesting structures in ASAL regions. In addition, findings between studies were also based on existing regional biophysical features, which implies that results from one region may not be applicable elsewhere (Adham et al (2016).

Environmental factors do not function in isolation; their combined effects may not be explained by assessing their individual impacts. As a response to interactions between environmental factors, the concept of AEZ may provide a useful guide for siting sand dams. Agro-ecological zones are regions that have exhibited homogenous climate, precipitation, physiographic factors, soils, vegetation and animal species. Key elements in defining an AEZ are growing period, temperature regime and soil type. The Food and Agriculture Organization and the International Institute for Applied System Analysis have developed maps of AEZs that considered interactions of similar factors and their influence on rain-fed crop yields (Fischer et al. 2002; Gunther et al. 2012). AEZ have been found to be reasonably good indicators of natural resources endowment and agriculture potential and in the formulation of strategies in soil conservation and fertility management, water harvesting, forest management and livestock development (FAO 2003).

Each AEZ has a specific range of potentials and constraints for land use (Berkat and Tazi, 2006; Sombroek et al. 1982). Kenyan agro-ecological zones were first outlined in Sombroek et al. (1982) and later revised by Jaetzold et al. (2006). The AEZ groups are temperature belts defined

Table 1 Factors that affect sand dams capacity to supply water

For a riverbed section to be considered suitable for siting a sand dam, it should fulfil a certain range of characteristics on its catchment as well as along the riverbed. These characteristics include

Soil textural characteristics: Sand dams should be sited along riverbeds with catchments whose soil is high in coarse sand (Nissen-petersen 2006). The texture of the sediments determines the specific yield of sand dams. Specific yield is the ratio of the volume of water that a saturated rock or soil will yield by gravity to the total volume of the rock or soil expressed as a percentage (Johnson, 1966)

Rainfall amount: Areas where rainfall is too little will not yield any runoff to the sand dams. It is the same runoff that is expected to bring coarse sand to the riverbed. Areas with rainfall amount totals of less than 200 mm p.a are considered unsuitable (Adham et al. 2016). This research assessed sand dams in rainfall amount above 400 mm p.a

Catchment topography: Level grounds that cannot support sediment generation and transportation to the riverbed are not good for sand dams construction (Mati et al. 2007). In (Hut et al. 2008), a topographical gradient of 2–4% is recommended although in some cases higher gradients have been used

Geology/Lithology: Sand dams should overlay a natural impermeable dyke downstream of an existing water hole. The impermeable hydraulic barrier can be made of rocks or clay layers. Presence of rock outcrops along the riverbed is viewed as an indicator of a hydraulic barrier

Section of the riverbed where water last for at least one month after other sections of the river have dried up already. This is one of the ways the local people are able to identify a naturally occurring dyke (Nissen-Petersen 2000)

Presence of water indicating vegetation along the riverbed. Water indicating vegetation has traditionally been used to locate sites where groundwater can be accessed and offers good indicators of an impermeable layer along the riverbed where a sand dam can be located to increase the amount of water stored (Nissen-petersen 2006) according to the maximum temperature limits, within which the major crops (maize, sunflower and cotton for Kitui County) in Kenya can flourish. Kitui county mainly falls in the transitional class 4 in the maize – sunflower upper midland (UM4) zone and marginal cotton zone in the lower midlands (LM4) (Jaetzold et al. 2006). Each unit has a different moisture index, which is the ratio of average annual rainfall for an area to average annual potential evapotranspiration in percentage form (Sombroek et al. 1982). In addition, rivers tend to converge and enlarge downstream increasing discharge. Downstream also have more subsurface flow entering the streams. To assess if this could have any correlation to dams ability to supply water during the drought periods, stream orders as defined by Strahler (1957) were included in the assessment as well.

With changes in environmental, anthropogenic, technological changes, even AEZs are not stable. A shift from high potential to low potential AEZs is attributable to climate change. In Kenya's lowland zones (including Kitui County), there has been an increase of 0.5 °C in temperature (Jaetzold et al. 2006), which negatively affects the moisture index and lowers the potential to meet growth requirements for crops. Tiva catchment has moisture indices ranging from 15–65% across four different types of AEZs (semi-humid, semi-humid to semi-arid, semi-arid and arid) (Table 2). Tiva's AEZs were analyzed to ascertain whether the interaction of factors that define the AEZs have any applicability in siting sand dams and whether the identified shifts in AEZs have any relevance on the ability of sand dams to supply moisture during the drought periods.

Materials and methods

The study site was Tiva Catchment found within Kitui County. The identification of this study site was preceded by a reconnaissance survey in the counties of Kajiado, Machakos and Kitui. Kitui county was preferred for this study because unlike Machakos and Kajiado, it was less affected by sand mining. Tiva river catchment in Kitui County lies between − 1.66 and − 2.67 S and 37.75 and 38.67 E degrees, respectively (Fig. 2a, b). The county ranges between 400 and 1800 m above sea level (Lasage 2015), with the western and central parts characterized by hilly ridges separated by wide, low lying areas. Most of the land area is within the Tana River drainage basin. Only a narrow strip along the south and southwest border drains to the Athi River. In 2009, Kitui County had a population of just over one million people, with Akamba people dominating. Its main economic activities are subsistence agriculture, beekeeping, small-scale businesses, dairy farming, and ecotourism. Agricultural products from the study area comprise of fruits (mangoes, pawpaws, watermelons), maize, cowpeas, beans, pigeon peas, lentils and livestock (cattle, sheep, goats and chicken). Donkeys and oxen are extensively used for draught power, fetching water, transport and cultivation. Other economic activities in the county include charcoal burning, brick making and basket weaving (Ngigi 2003).

This study assessed 116 sand dams in October 2016 with 89 being within Tiva catchment, while the rest mapped just outside of the catchment boundary. October is generally the driest month of the inter-seasonal drought between long and short rains. The 89 sand dams were about 30% of the estimated 300–400 sand dams within Tiva river catchment, a number considered representative according to Mugenda and Mugenda (2003) and Borg and Gall (2003). A questionnaire was filled through interviewing sand dams' beneficiaries and sand dams' management committees whose coverage also considered gender balance. On each dam site, three dam beneficiaries were identified and interviewed. Data collected using the questionnaire at each dam site included socio-economic data, community water demand, the extent to which the sand dams met community water requirements, the time community stopped obtaining water from the sand dams and presence of sub-surface water for at least one month after the rains at the site where the sand dam was constructed. The information gathered through the questionnaire was clarified through observations and measurements in the field. The next sand dam was identified through snowball method where those interviewed directed the survey team to the next site. The geographical locations of dams were taken using a global positioning system (GPS) device and mapped onto the Kitui county map using geographic information system (GIS) software ArcMap. Geo-referenced maps of Kitui for factors that determine sand dams' performance were acquired in form of raster images from the Regional Centre for Mapping of Resources for Development, Nairobi (RCMRD) and the Survey of Kenya. They included

Table 2 Agro-climatic zones in Tiva catchment (Sombroek et al. 1982)

Agro—Climatic Zone	Classification (Temp zone)	Moisture Index (%)	Annual Rainfall (mm)
III	Semi-humid (20–22)	50–65	800–1400
IV	Semi-humid to semi-arid (22–24)	40–50	600–1100
V	Semi-arid (22–24)	25–40	450–900
V	Semi-arid (24–30)	25–40	450–900

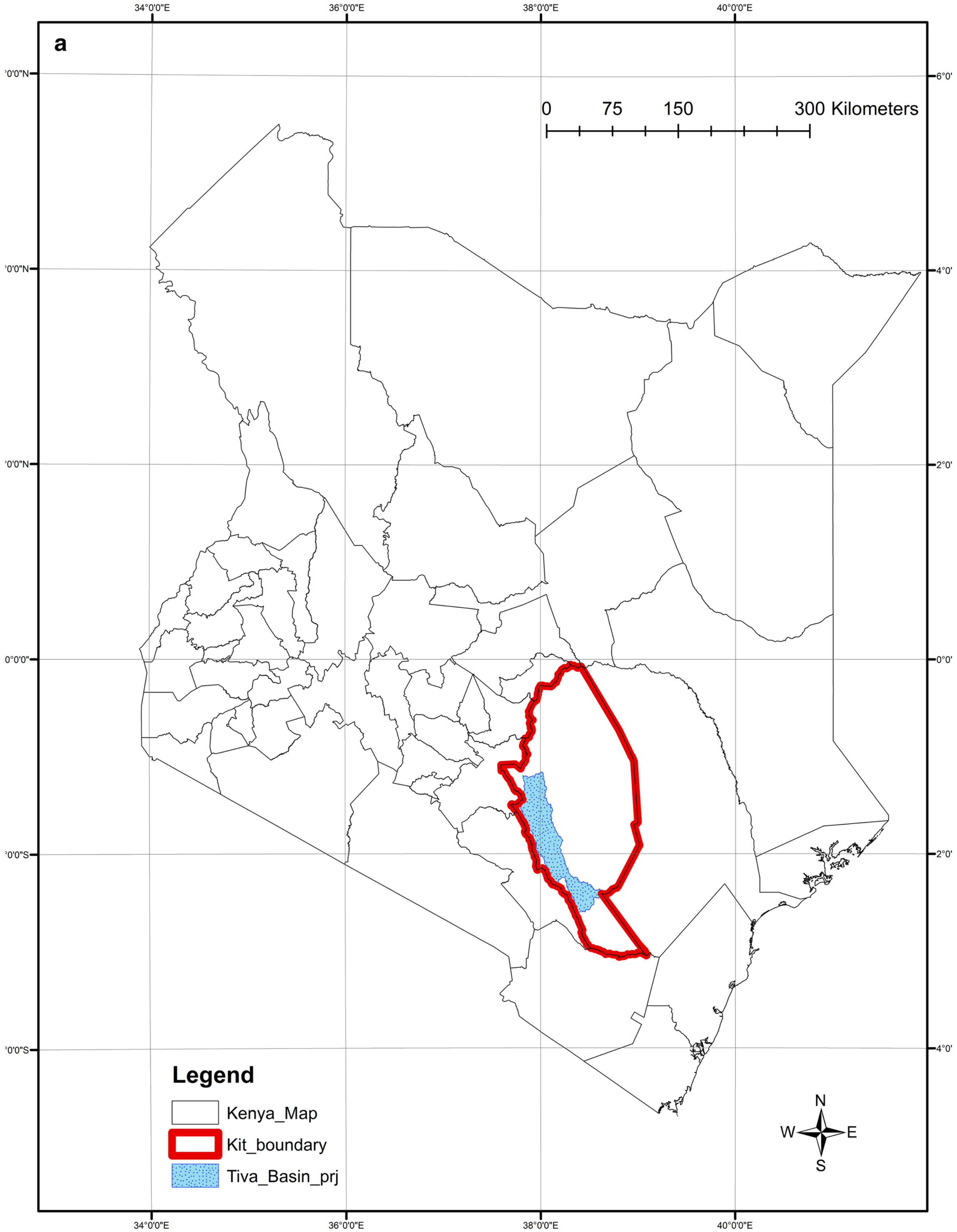

Fig. 2 **a** Map of Kenya showing Tiva Catchment within Kitui County. **b** Map Tiva Catchment within Kitui County

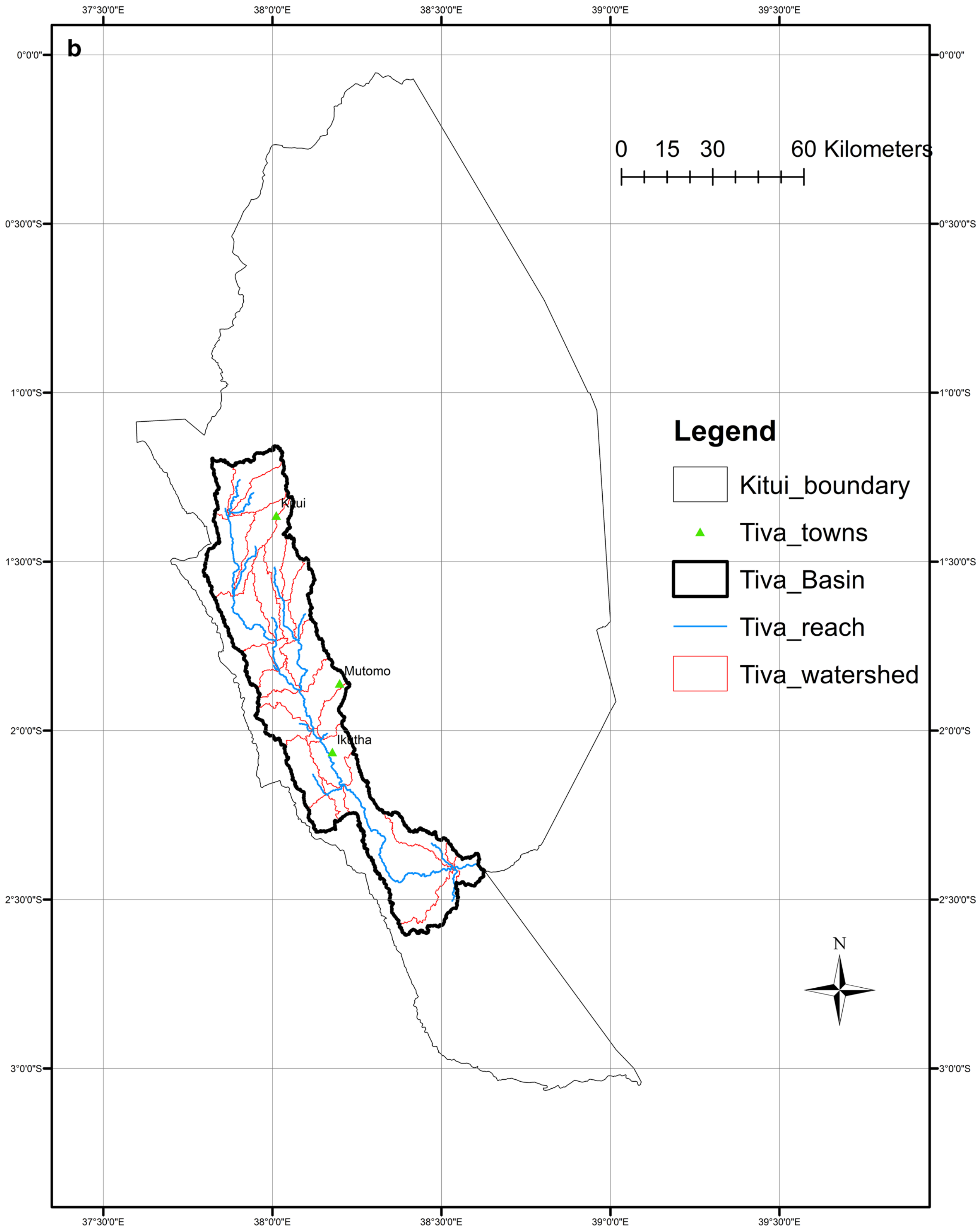

Fig. 2 (continued)

soil type, rainfall, digital elevation model from which catchment topography and stream orders were generated, geology/lithology and AEZ of 1982 and 2006. Details for the acquisition of each of the factors are listed in Table 3.

Data on socio-economic factors within Tiva catchment and sand dams' ability to supply water from the questionnaire were analyzed using Statistical Package for the Social Sciences (SPSS) 22. Descriptive statistics such as frequencies, mean and percentages were used to describe population characteristics of user communities of sand dams. The raster images for soil, rainfall, topography, geology/lithology and stream orders were analyzed through creating polygons matching the different ranges. This was followed by overlaying the sampled sand dams whose ability to bridge water access gap had already been determined during the field survey. Interaction of these factors was analyzed with AEZ developed by Food and Agriculture Organization (FAO) and International Institute for Applied Systems Analysis (IIASA) (Sombroek et al. 1982) and revised by Jaetzold et al. (2006).

Results and discussion

Dams and water use

All the 116 assessed sand dams were made of masonry walls. Their average length (width of the sandy riverbed) was 26.9 m, with the shortest being 9 m and the longest 69.7 m. The largest percentage of sand dams (35.7%) were in the 20–30 m length range, followed by 10–20 m at 29.8%. Overall, 86.9% of the sand dam lengths were 40 m and below. Dam height showed a mean of 1.46 m, measured from foundation to the crest at the middle of the riverbed on the downstream. The standard deviation (std) was 0.58 m with 0.45 m being shortest and 3.00 m the tallest. Dam height measurement was not always possible where the dam foundation was covered by sediments. Spillways of dams were the shortest (Fig. 1). The spillways direct flash floods within the river bed and prevent water from digging around the dam walls. Two different shapes were used, compound rectangular and trapezoidal. Wall width measured 0.77 m on average with std 0.17 m, the thinnest wall of 0.42 m and a thickest 1.04 m. Some sand dams had an apron immediately downstream to prevent undercutting of the foundation (which was found to be a problem with some of the sand dams).

The number of households depending on each sand dam varied (Fig. 3), with some dams supporting over 400 households. Most dams (42.4%) supported up to 50 households. Households moved from sand dams whose subsurface water got depleted to those that would be having water, which could mean that the same household was counted more than once. Average family size within Tiva catchment was 5.98 (with std 2.6) persons. Most households kept livestock which included cattle, sheep, goats, chicken and donkeys. The livestock was a source of food, organic manure and income. Donkeys and oxen were used as draught animals. Some 35% of dams were utilized for minor irrigation with irrigating vegetables done by men alone (4.3%), women alone (6.8%) or both sexes (23.9%). Vegetables were for home consumption and sale alike. 63.2% of the dams supplied water for making bricks, a male-dominated activity for income generation. Brick making in most cases took place soon after the rains when most dams contained water while irrigation took place near dams that provided water on a perennial basis.

Most critical water requirements for households in the Tiva area were, therefore, based on water for human and livestock consumption. Human water requirements were taken as the World Health Organization WHO recommendation of 20 L of water per day per person (Manyanhaire and Kamuzungu 2009). Each household required an average of 119.6 (5.98 × 20) and 119.3 (Table 4) liters or approximately 240 L of water for both human and livestock consumption, respectively, per day. The required water supplying capacity for a dam supplying water to 50 households is given in Box 1, considering water requirements for both human and livestock consumption and the more severe drought of June to October totaling about 150 days.

Table 3 Indicators considered when siting sand dams

	Factors	Standard guidelines	Source
1	Soil type	High in sand content (Based on guidelines by FAO (2006) (Sand; 0.063–2 mm, Silt; 0.002–0.063 mm, clay, < 0.002 mm)	Survey of Kenya
2	Rainfall amount	Medium to high ≥ 200 mm	RCMRD
3	Topography	Catchment slope 2–4%	DEM from RCMRD
4	Geology/Lithology	Impermeable riverbeds	RCMRD
5	Rock outcrop	Presence of rock outcrops	Field survey
	Agro-ecological zones of 1982 and 2006	Not defined	RCMRD
	Stream orders	Not defined	DEM from RCMRD

Fig. 3 Number of households per sand dam

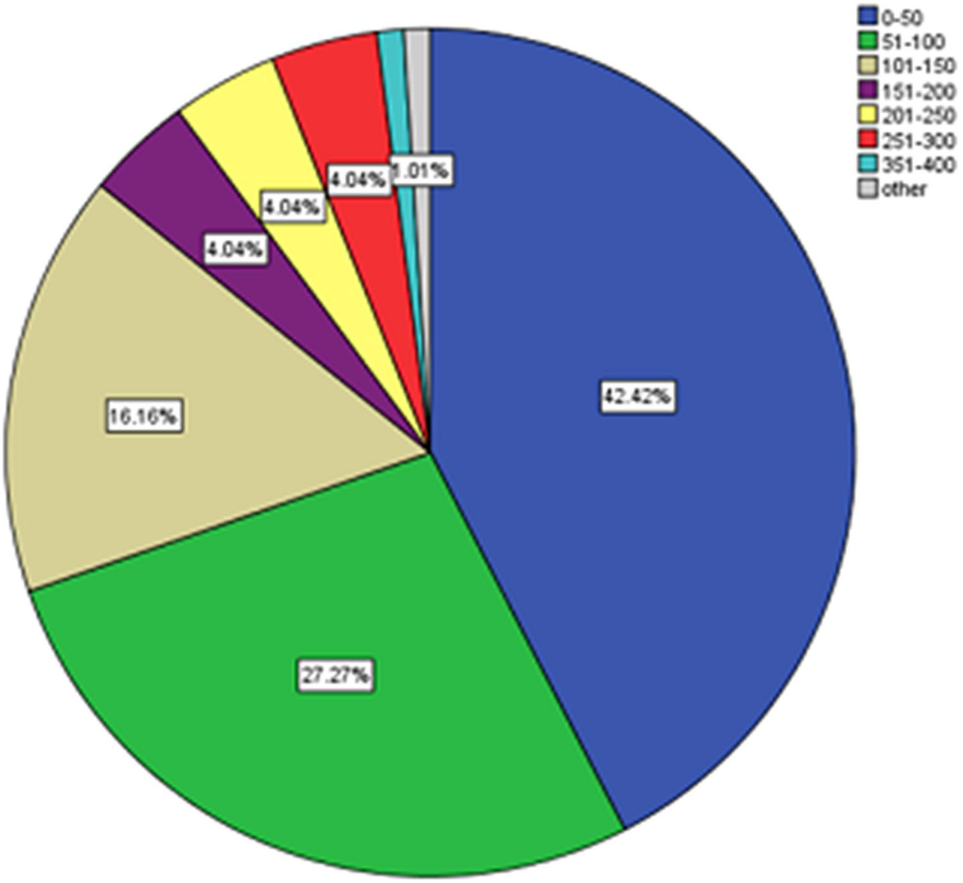

Table 4 Livestock ownership and daily average (avr) water requirement (liters) per livestock unit (LU) and household (HH) within Tiva catchment

No. of livestock per HH	With	Without	Minimum	Maximum	Mean	LU rate	Avr LU	Avr daily water demand
Cattle	65	53	1	30	3.88	0.7	2.716	67.9
Sheep and goats	85	33	1	40	8.84	0.1	0.884	22.1
Chicken	95	23	1	100	13.04	100 = 1Lu	0.1304	3.26
Donkeys	70	48	1	4	1.49	0.7	1.043	26.075
Total daily average household water demand for livestock use								119.335

Box 1 Required dam water supplying capacity for 50 households

Box: Water requirement (m^3) for human consumption from June to October.

$$\frac{50h \times 5.98p \times 20l/c \times 150d}{1000} = 897\mathrm{M}^3 \tag{1}$$

where;

h Household

p Persons per households

l/c daily per capita water requirement in liters

150*d* being the duration of the more severe drought of June to October.

With these numbers, a sand dam supplying water to 50 households should supply some 900 m^3 of water for human consumption and another 900 m^3 for livestock use, totaling 1800 m^3 evenly distributed throughout the longer inter-seasonal drought of June to October or the less severe drought period of December to March. Actual water supply capacities per dam can range from 1000 m^3 (Nissen-Petersen 2006) to 2800 m^3 (Quilis et al. 2009; Hut et al. 2008). The field assessment

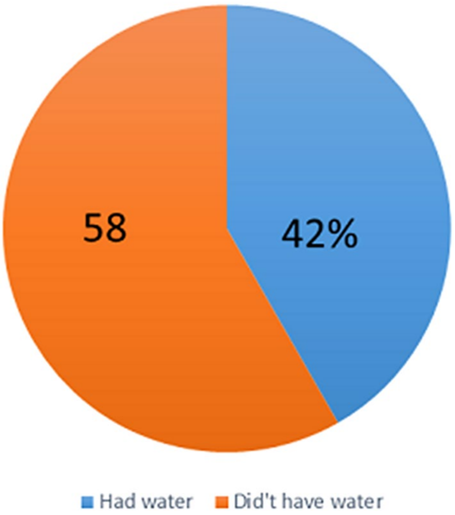

Fig. 4 Percentage of sand dams with and without water during the assessment

showed that about 42% of the dams could meet household water demand throughout the drought period. However, 58% of the dams could not (Fig. 4). Figure 5. Shows that by the end of the drought period between short and long rains, only about 43% of the dams would have water. The corresponding number for the other dry season was even lower at 36% of dams assessed.

Figure 5 shows that 16% of the dams after the short rains and 23% after the long rains became dry soon after the rains stopped. Dry dams leave water users with the challenge of identifying alternative water sources, including other sand dams or riverbeds, hand dug or shallow wells, springs, water tanks from household roof rainwater harvesting, earth dams, boreholes and in some cases piped water (Fig. 6). Some of the households near Kitui town benefited from piped water from Masinga dam, the main hydro-electric generation water reservoir in Kenya. Overall, search for water in Tiva catchment was a time-consuming activity as Fig. 7 shows. About 21% of the households walked up to 3 h in search

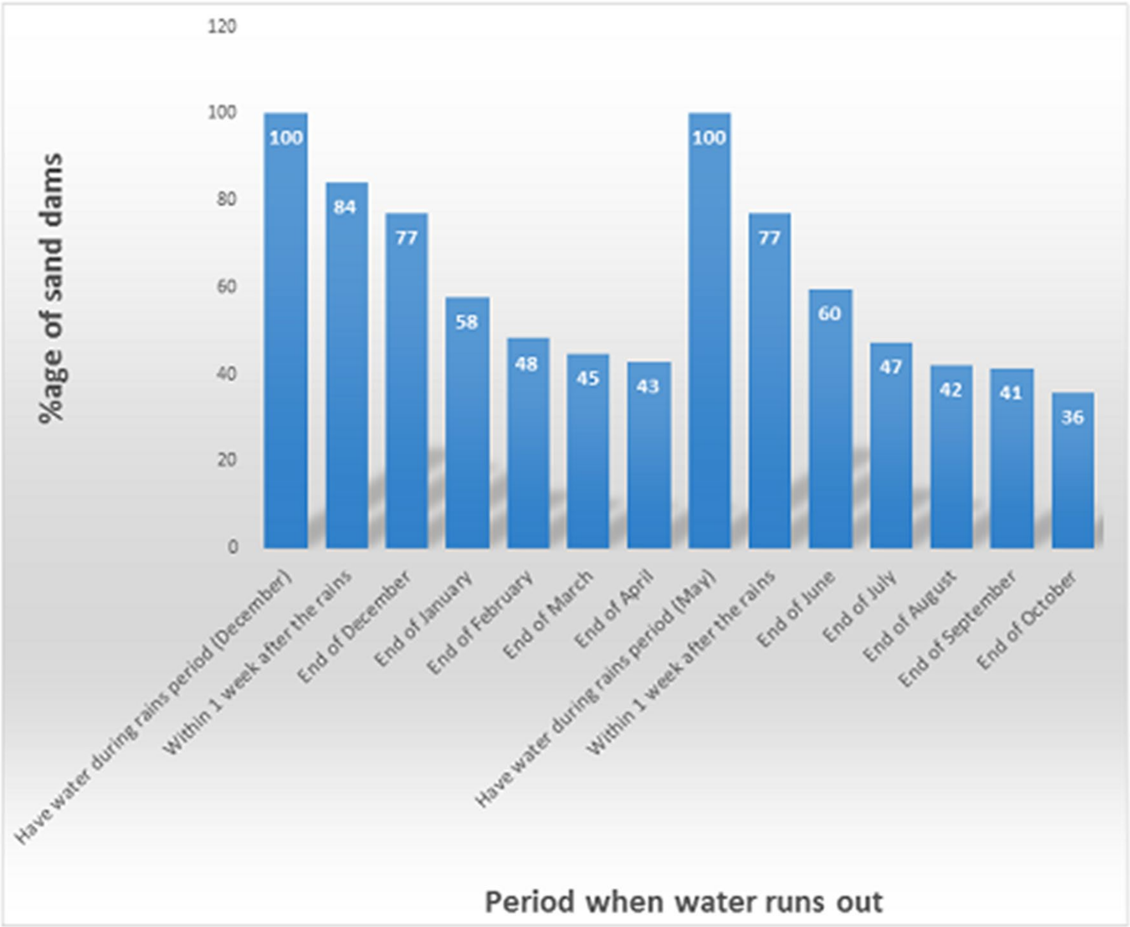

Fig. 5 Percentage of sand dams with water per month following the short and the long rainy seasons

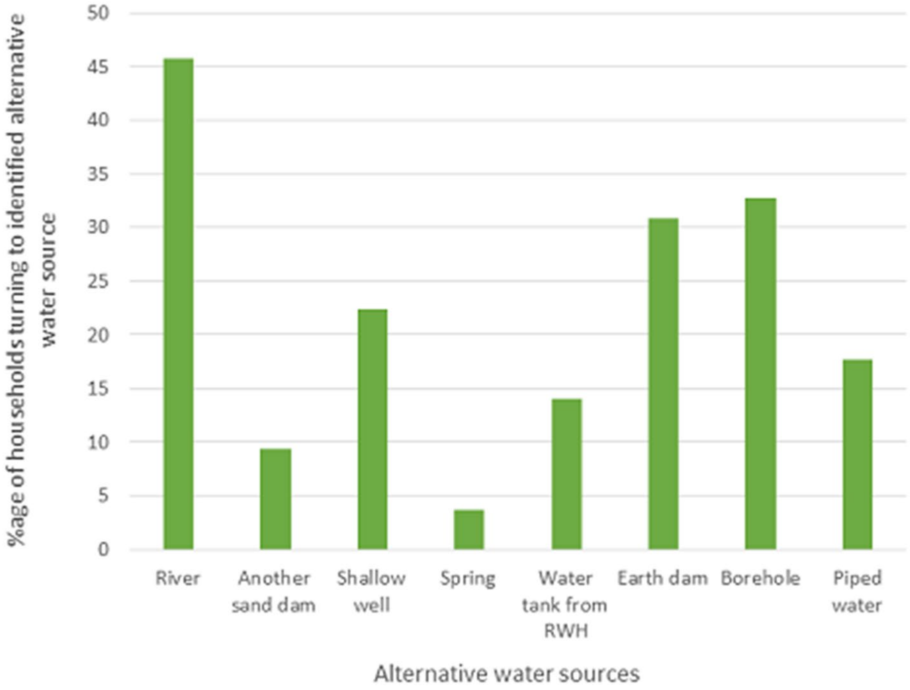

Fig. 6 Alternative water sources within Tiva catchment

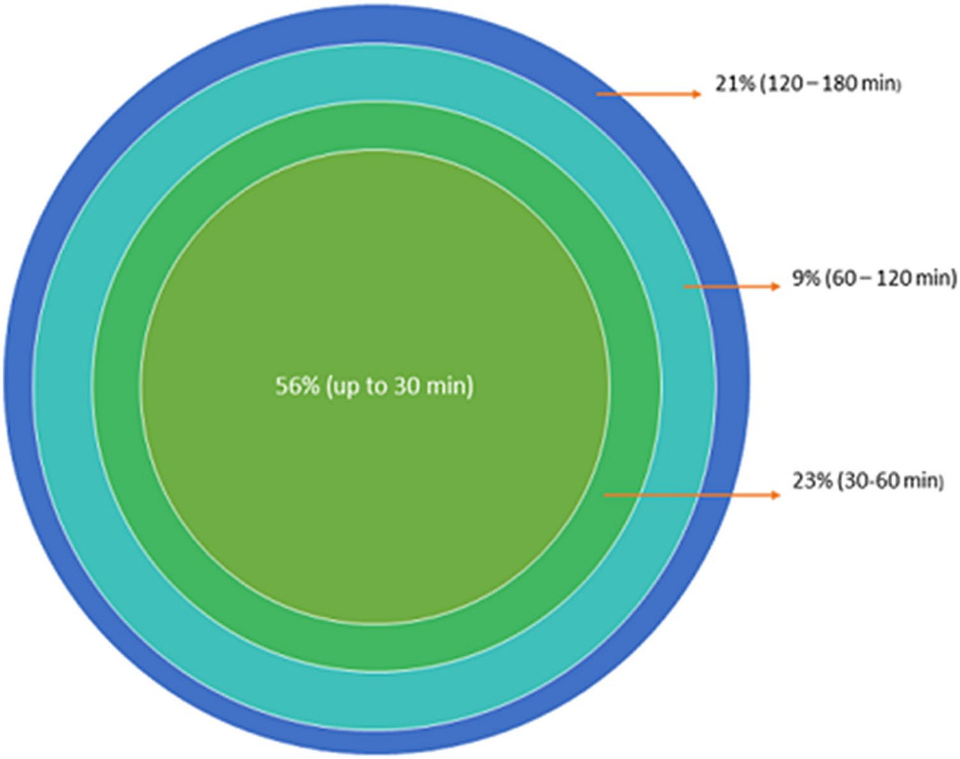

Fig. 7 Time households spent to reach alternative water sources after sand dams dry up

of water. The majority (56%) found alternative water sources within 30 min walking distance, carrying the water to their homes in 20–25 L plastic containers on people's backs, mainly women, or on donkeys or oxen.

Below, the possible influence of the factors mentioned above on the ability of sand dams to supply water during the inter-season drought periods are discussed. The results are outlined in Figs. 8, 9, 10, 11, 12, 13, 14 and Tables 5, 6, 7, 8, 9, 10, 11. First, we present the

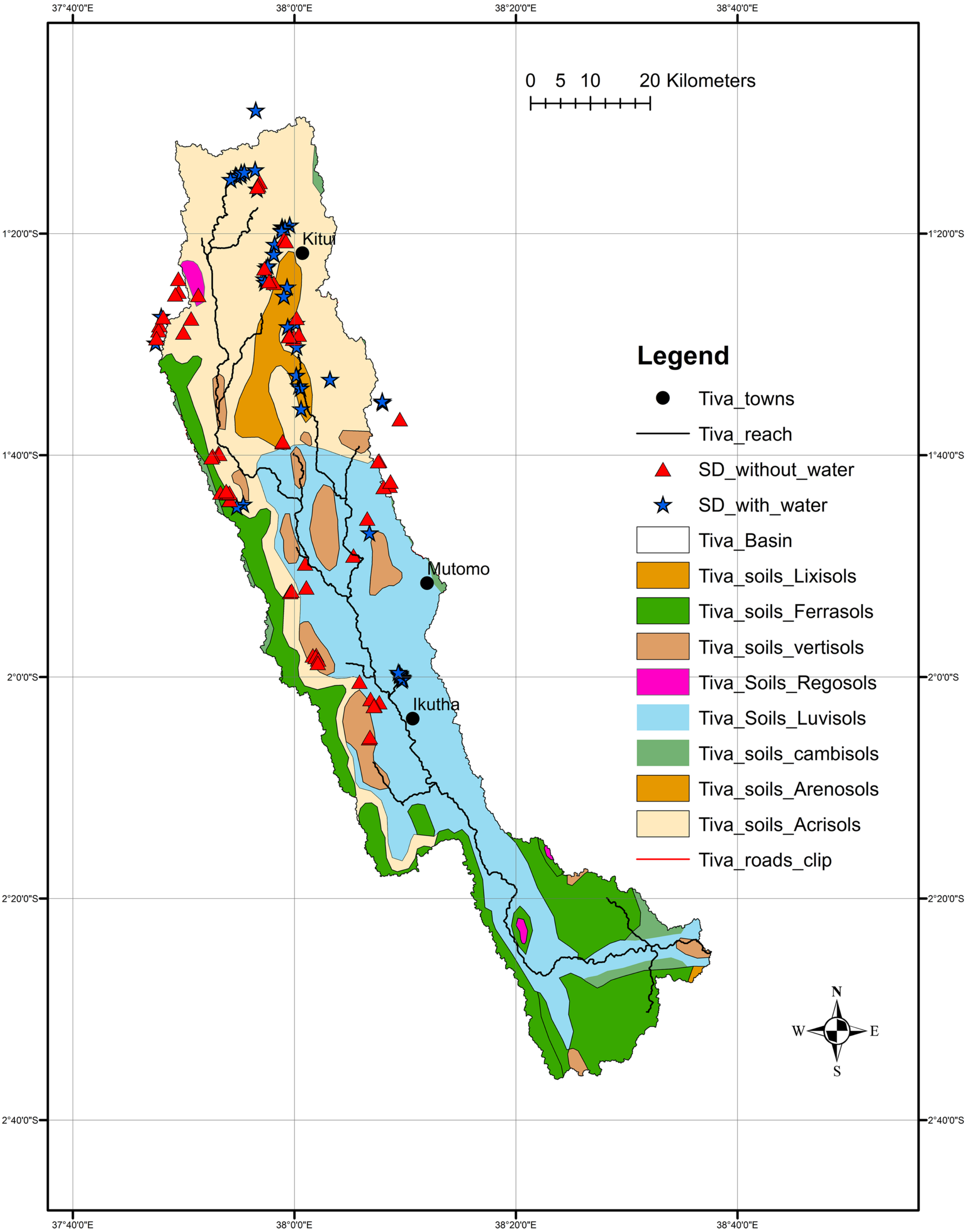

Fig. 8 Sand dams with and without water in the shown soil types

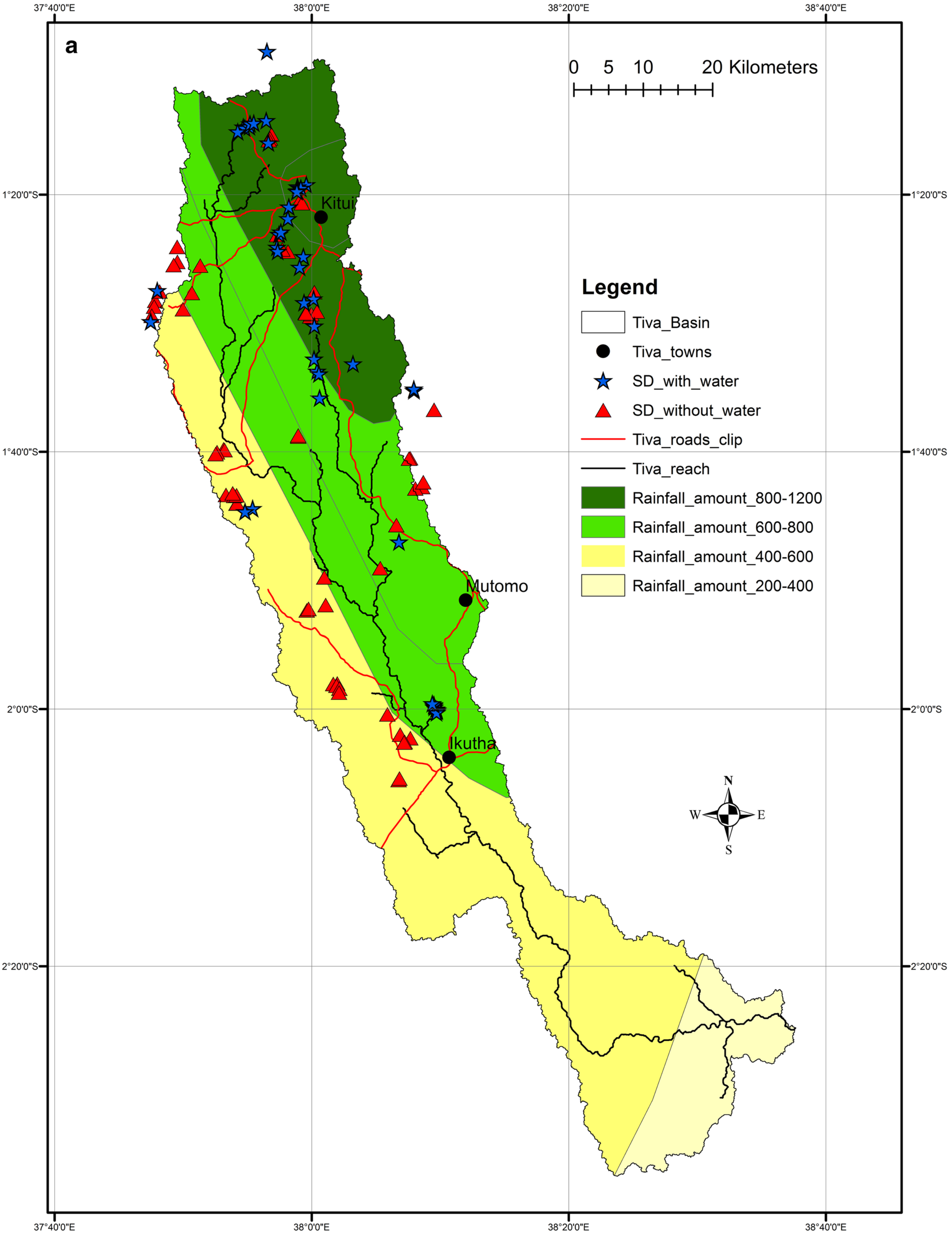

Fig. 9 **a**, **b** Sand dams with and without water within the defined isohyets (SD = Sand dam)

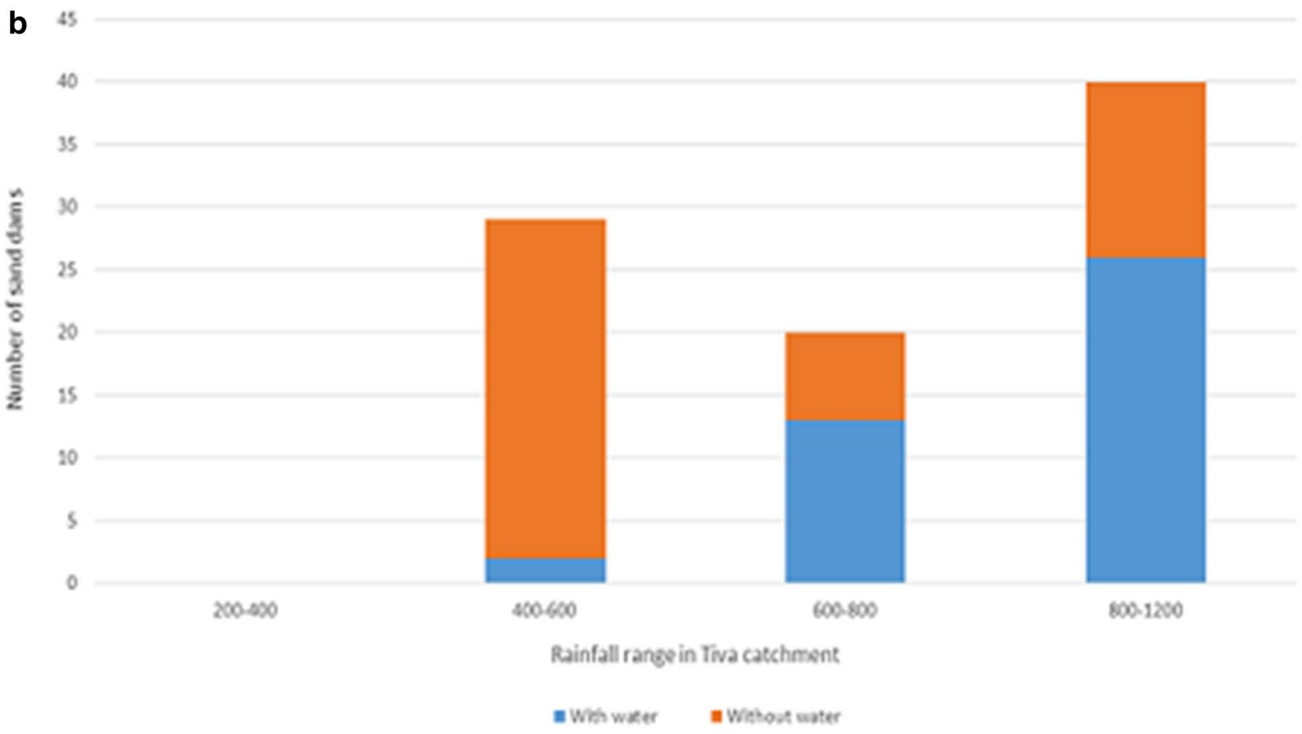

Fig. 9 (continued)

results of single factors (soil, rainfall, geology, topography, water and vegetation. Second, we present two factors on a landscape level, which combine the effects of single factors. These two landscape factors are agro-ecological zones and stream order.

Single factors

Soil

Sand dams in riverbeds whose catchment contained Vertisols and Ferrasols soils show less likelihood of supplying water during drought periods while Arenosols show opposite results. Sand dams numbers found with and without water are shown in Table 5 and graphically displayed in Fig. 8. Acrisols, with most dams, show equal numbers for dams with water and without water. Most dams were constructed in high sand content regions (60% and above), but many of them did not have water during the assessment. Likewise, most dams were constructed in regions that had less clay content, but many dams did not have water during the assessment. A high catchment clay content showed reduced dam ability to supply water during the drought period (Table 6). No sand dams were found in regions with silt contents over 20%. Communities and developers of sand dams will not construct a sand dam in regions where the river sediments do not contain coarse sand. This could be the reason a region with high silt content may not have dams. Silt may cause more clogging of pore spaces of sand in dams compared to clay due to the lower amount of energy required to flush out clay particles.

Rainfall

The likelihood of a sand dam providing water increased with an increase in rainfall amount (Fig. 9a and 9b). In the lowest rainfall category, dams were not encountered. The long rains (March—May) amount for stations 9,138,013 (Ikanga Chief's camp and 9,138,001 (Mutomo Agricultural Station) both in the rainfall range 600—800 mm) was, 168.5 and 161.1 with 56% and 45% probability of exceedance, respectively. This implies the rainfall amount for the season was not unusual.

Geology

Most of Tiva catchment comprises of metamorphic rock. Igneous rocks may be better at retaining water in the riverbed but are limited in extent (Fig. 10 and Table 7).

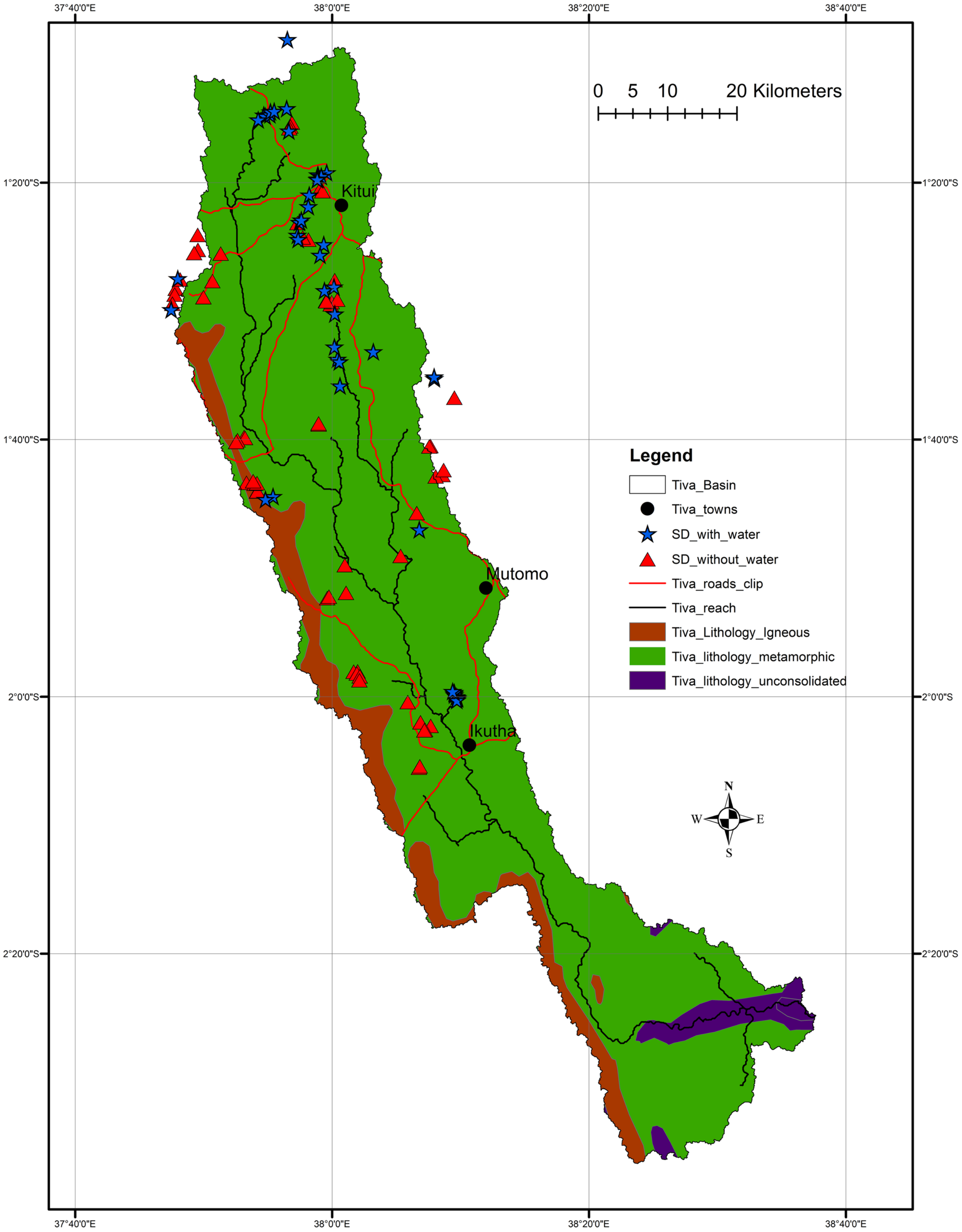

Fig. 10 Sand dams with and without water within different rock types in Tiva catchment (SD = Sand dam)

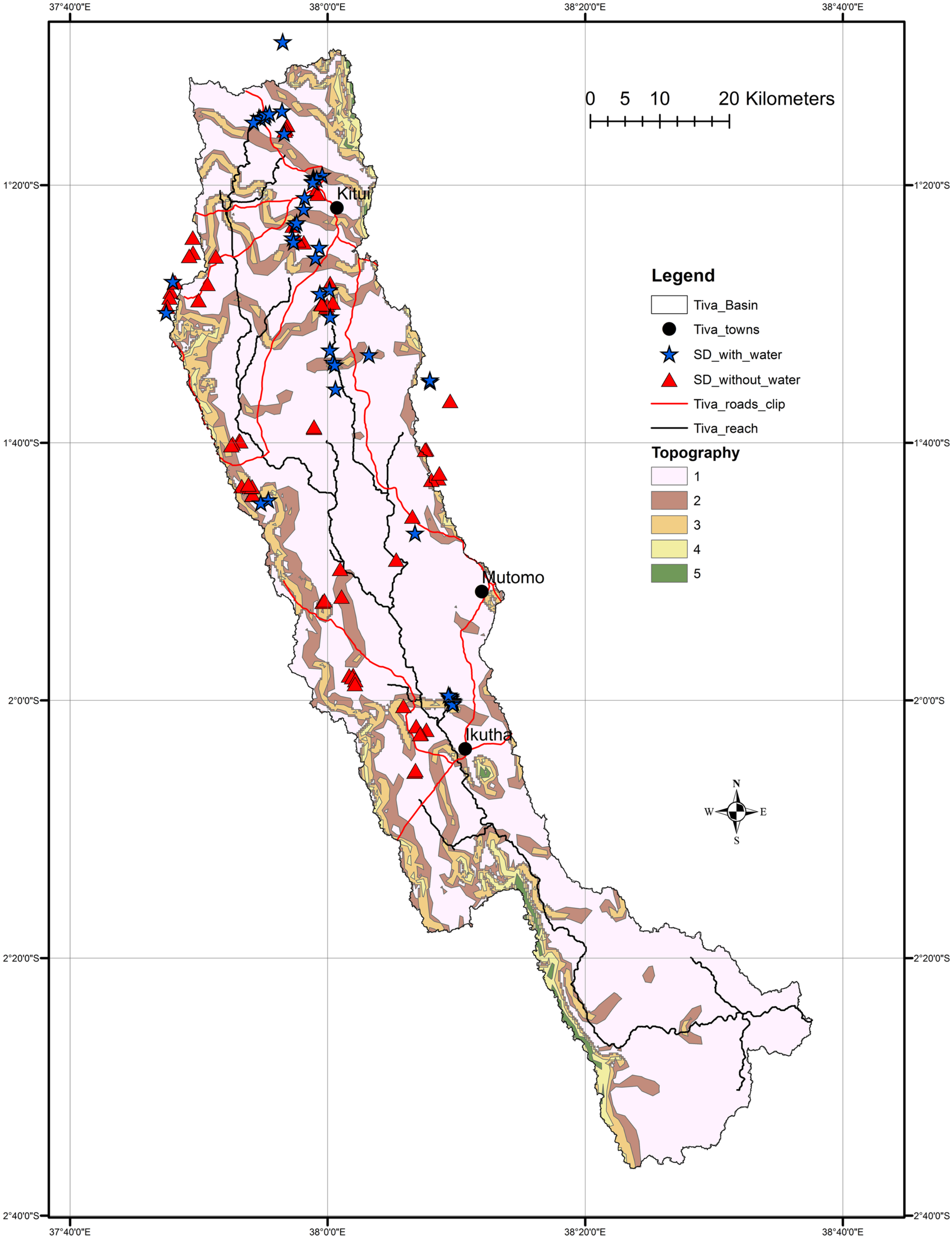

Fig. 11 Topography and sand dams with and without water (SD = Sand dam)

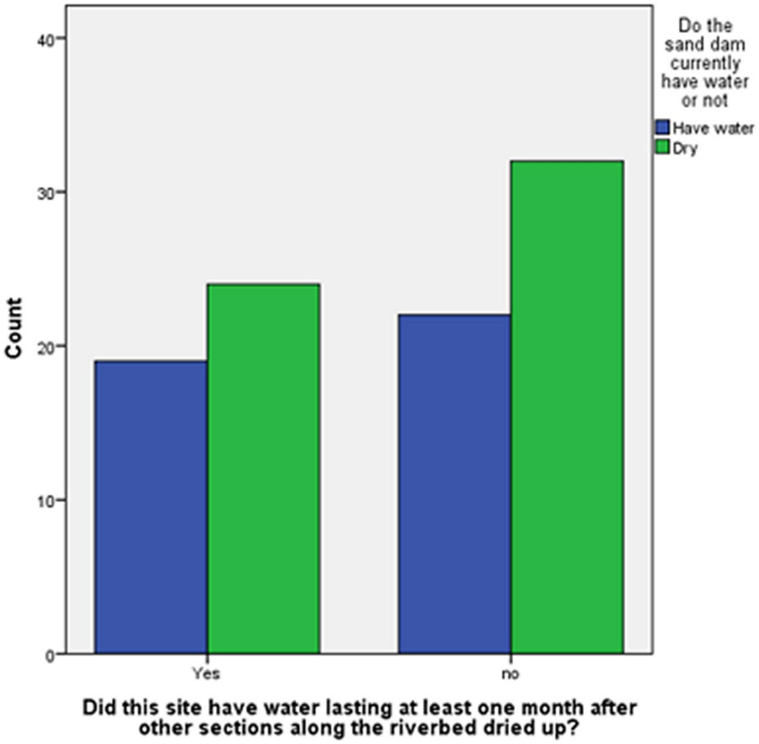

Fig. 12 Sand dams with and without water for locations with or without sub-surface water lasting at least one month after it got depleted in other parts

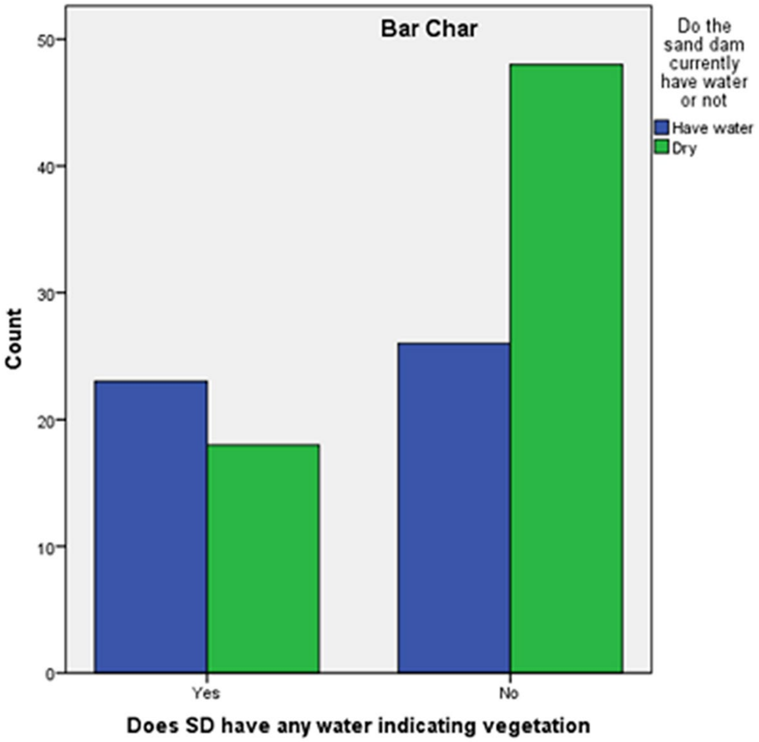

Fig. 13 Comparison of sand dams with and without water in riverbeds with and without water indicating vegetation

Presence of rock outcrops marginally increases the likelihood of a site to retain water, as 34 out of 75 sand dams that had rock outcrops and 14 out of 36 that did not have rock outcrops, respectively, had water (Table 8). As Table 8 shows, sand dams with rock outcrops retain water for longer periods compared to those without. This corresponds with results from the questionnaire showing 36% of dams being perennial.

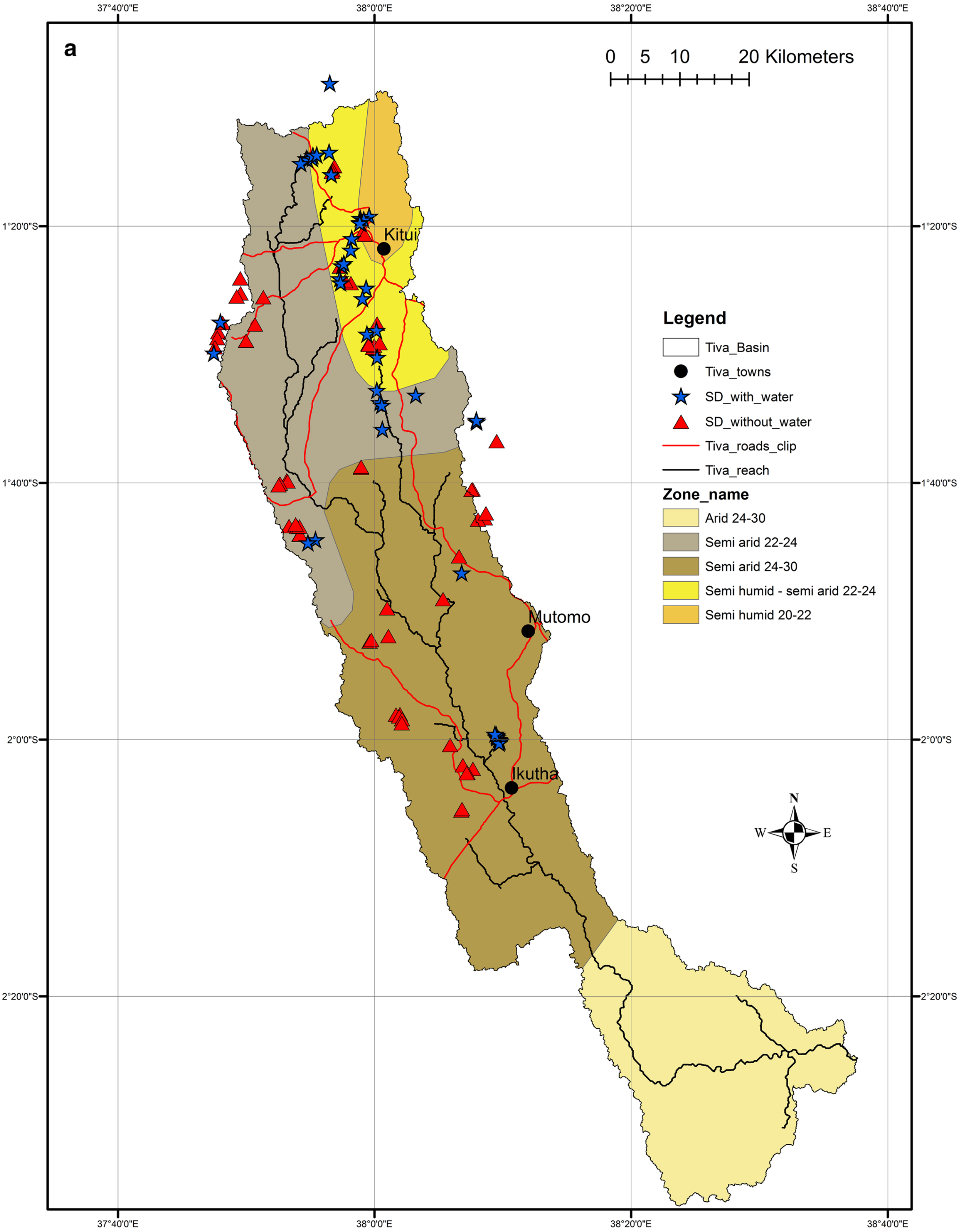

Fig. 14 **a** Sand dams with and without water within different agro-ecological zones of 1980 (SD = Sand dam). **b** Sand dams with and without water within different agro-ecological zones of 2006 (SD = Sand dam)

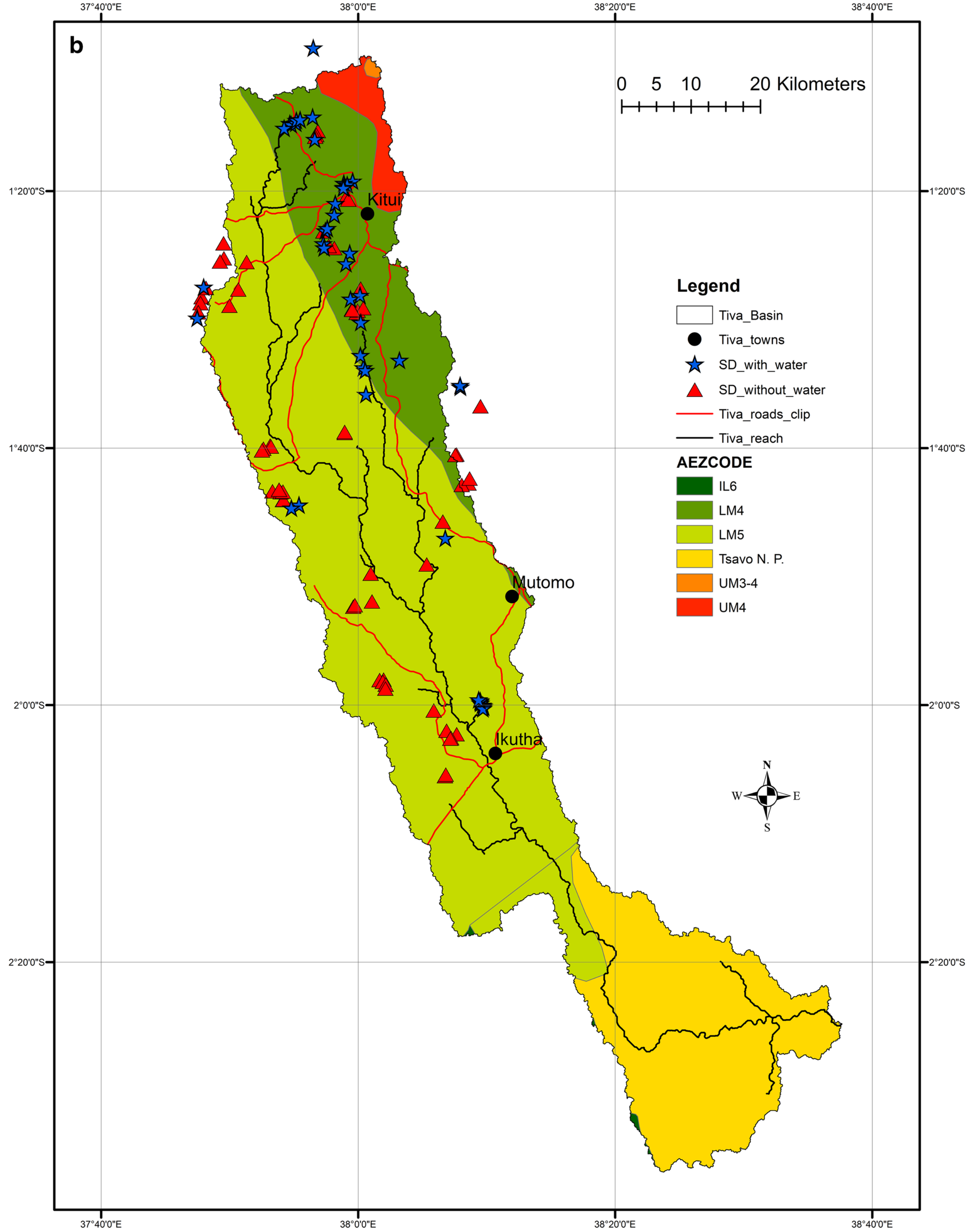

Fig. 14 (continued)

Table 5 Sand dams with and without water in the listed soil types

Soil type	With water	Without water
Acrisols	24	23
Arenosols	6	2
Cambisols	0	0
Ferralsols	1	6
Lixisols	0	0
Luvisols	10	9
Regosols	0	1
Vertisols	0	7

Topography

Most sand dams were built within a catchment slope of 1%, with many dams having and not having water. Higher catchment slopes showed less likelihood of dams providing water during drought, with 8 out of 9 dams in the 2–5% range not having water during the assessment (Fig. 11 and Table 9).

Water

Whether sub-surface water was present in a portion of the riverbed for about a month after it got depleted in other sections prior to sand dams construction is presented in Fig. 12. Such sites do not offer any guarantee there will be water throughout the drought period as less than half of such sites were found with sub-surface water.

Vegetation

More than half of the dams on sites with water indicating vegetation had water. On sites that did not have such vegetation, less than half of the sand dams did not have any water during the assessment (Fig. 13). Hand-dug wells were fitted to some of the dams to access aquifers recharged by the dams. Out of 41 dams with water indicating vegetation, only 18 were equipped with wells.

Table 7 Sand dams with and without water within different rock types in Tiva catchment

Lithology	With water	Without water
Igneous	1	6
Metamorphic	40	42
Unconsolidated	0	0

Table 8 Rock outcrops and gradual reduction of water from sand dams

Month water last after October rains × Does the SD have rock outcrop Cross-tabulation

		Does the SD have rock outcrop		Total
		Yes	No	
Month water last after October rains	Never dries up	34	14	48
	No water held	12	6	18
	December	5	3	8
	January	12	10	22
	February	6	3	9
	March	4	0	4
	April	2	0	2
Total		75	36	111

Combined factors

Agro-ecological zones

Regions with higher potential for rainfed agriculture are also more likely to have dams with water. Number of sand

Table 6 Sand dams with and without water in soils with different sand, silt and clay content

% Age sand	Sand dams		% Age clay	Sand dams		% Age silt	Sand dams	
	With water	Without water		With water	Without water		With water	Without water
≤ 17.5	0	7	≤ 15	6	2	≤ 10	11	14
17.5 – 32.5	11	14	15–17.5	24	24	10–12.5	0	7
32.5–35	0	0	17.5–25	0	0	12.5–15	6	2
35–47.5	0	1	25–30	0	1	15–20	24	24
47.5–55	0	0	30–35	0	0	20–22.5	0	1
55–60	0	0	35–37.5	0	0	22.5–30	0	0
60–62.5	24	24	37.5–57.5	11	14			
62.5—70	6	2	57.5–70	0	7			

Table 9 Topography and sand dams with and without water

Slope	With water	Without water
≤ 1%	36	35
1–2%	4	5
2–5%	1	8
5–10%	0	0
10–20%	0	0

Table 10 Sand dams with and without water within different agro-ecological zones of 1980

Agro-Ecological zone	With water	Without water
Arid (24–30)	0	0
Semi-arid (24–30)	10	14
Semi-arid (22–24)	10	20
Semi-humid-semi-arid (22–24)	16	12
Semi-humid (20–22)	5	2

Table 11 Sand dams with and without water within different agro-ecological zones of 2006

Agro-Ecological zone	With water	Without water
IL6	0	0
Tsavo National park	0	0
LM5	13	34
LM4	28	14
UM4	0	0
UM3-4	0	0

dams within each zone are indicated in Tables 10 and 11 and graphically displayed in Fig. 14a and b.

Stream order

The stream orders for Tiva river and its tributaries stretched from one to seven. Sand dams were found in stream orders 1–5. 11% of the sand dams had been constructed on stream order one. The corresponding percentages for 2, 3, 4 and 5 stream orders were 31%, 35%, 19% and 4%. Stream order three had the largest number of dams and cumulatively, stream orders 1–3 had a total of 77%. All dams built-in stream order one did not have any water. 75% of those in stream order 2 did not have water. Close to 80% of those mapped on stream order 2 and 3 did not have water. This number changes for stream order 4 were about 70% of the dams built had water with a marginal increase to 80% for sand dams built-in stream order 5. Thus the percentage of those without water decreased to 20% at stream order 5. There were no sand dams found in stream orders 6 and above. Furthermore, high stream orders have water in the subsurface even without the presence of sand dams and probably do not attract the need to build sand dams.

How criteria do (not) predict the success of sand-storage dams

Our results suggest that ascertaining where sand dams will result in increased access to water for households during drought periods is difficult. Most of the dams were found without subsurface water during the assessment indicating they were incapable of providing water for community use throughout the drought period. Water was depleted in several dams within the first week after rainfall. Those that did not supply water as intended were either broken, often with river banks swept away, or simply dry. Despite a large number of failing dams, the assessment did not allow drawing consistent patterns in terms of explanatory factors for water availability in sand dams.

Soil

Even though the number of dams without water was higher for regions with low sand content, it is impossible to determine what soil sand content is critical for sand dams to function as water storage facilities during drought periods. Regions with a very high sand content of above 60% showed equal numbers of dams with and without water. As such, the presence of high percentages of coarse sand in a catchment may not result in increased water access throughout dry periods, a result that resonates with findings by Gijsbertsen (2007). To supply water from dams, water should be kept in and prevented from draining away from dams. There may be a need to line the riverbed of dams with an impermeable material before filling up with sand (or fill back) to ensure the bed holds water. In 1994, the Xiaoqinggou sand dam (Inner Mongolia, China) was lined with a geomembrane. It still provided water 10 years later (Jiang and Shi, 2004). Lining may be too costly or labor demanding but may provide an alternative to water losses through seepage.

Most sand dams were located on acrisols, with a sandy-loamy surface soil and low-activity clay accumulation in the B-horizon. For those soils, however, dam success is not guaranteed. The number of dams with and without water does not differ for regions with low clay content, which is against expectations. Whether a dam will contain water may, therefore, not be predicted by textural soil characteristics. Tiva's dams were built on riverbeds that already had course sand, implying that dam catchments may have had enough sand to fill the dams under the prevailing environmental factors. Nevertheless, using the sand content in Tiva catchment does not allow to predict whether sand dams are likely to supply water throughout the drought period.

Clay-richer soils show a pattern, as higher proportions of clay in catchments is negatively correlated to dams' ability to hold water, with Tiva's vertisols and ferralsols showing poor dam abilities to supply water, possibly due to siltation problems as observed by De Trincheria (2016) and Diettrich (2002). Whatever the reasons for reduced dams' capacities, solutions could be sought with some examples to learn from. In the USA, seepage loses and low specific capacity of sediments have been countered with subterranean soil-free reservoirs (Sivils and Brock 1981; Bliech and Weaver 1983) involving perforated, large-diameter pipes within the dam that were recharged every time it rained.

Geology

The lithology of Tiva catchment is dominated by metamorphic rocks. 82 dams were built in regions with metamorphic rocks; about half of them did not have water during the assessment. On the extreme western strip of Tiva catchment, the igneous rocks hosted seven dams, six of which were found with water. Igneous rocks may offer better prospects than metamorphic rocks, but igneous rocks are limited in extent and, therefore, usually unavailable. Existing guidelines by some of the developers for identifying suitable sites for constructing a sand dam recommend sites with rock outcrops that form an impermeable layer. 75 dams were found to have rock outcrops, out of which 35 (46%) had water, while 41 (54%) did not have any. 36 dams did not have rock outcrops, out of which only 13 (35%) had water. This may indicate that rock outcrops within the riverbed increase the likelihood of a sand dam to provide water, but are not definite proof that such a site will do so.

Rocks should be impermeable and non-porous but could have faults or cracks as well – something not easy to investigate by local communities or developers. Nissen-Petersen (2006) cautions on where to put the dam wall in relation to outcrops, noting boulders are unsuitable as they are not watertight. Instead, sand dams should be built on solid bedrock base or keyed one meter into solid and impermeable soil downstream of a naturally occurring depression. The knowledge on how to distinguish between boulders and rock outcrops is, therefore, important. Consequently, it is necessary to seek the services of a qualified geologist before sand dams are constructed. A general risk associated with rocks along riverbeds is mining by the construction industry, which already mines sand from sand dams, especially near urban centers. During this assessment, though not the focus of this study, 44% of the dams were affected by sand mining – although quantities withdrawn were low. However, sand mining seems to be slowly creeping in as they search for sand expands from the urban centers.

Water

Communities identified the presence of an impermeable riverbed through observing sub-surface water in a spot along the riverbed for at least one month after it got depleted in other parts. However, for dams meeting this criterion, almost equal number of sites with and without water were found (44.2% versus 40.7%). This suggests this criterion is not guiding site selection. In some of the sites, community members complained of water drying up after the dams were constructed, possibly as a result of sedimentation. Perhaps undisturbed riverbeds were not prone to sedimentation, while those with dams progressively trap fine-textured soil to a point such regions lose their porosity (De Trincheria 2016). Pauw et al (2008) and Mutiso (2010) report on cases where water quantities reduced progressively over the years after dams were constructed.

Topography

Most of Tiva catchment is gently sloping with a gradient of up to 2%. Gijsbertsen (2007) found that from the 3 criteria geology, topography and rainfall, topography was most important in identifying suitable sites. This study cannot confirm this finding. No clear patterns could be identified on how slope influenced sand dams' ability to supply water. However, steeper slopes may cause dams to fail as most dams within a 2–5% slope were dry. Steep slopes were encountered in regions where rivers were mostly young, which could have affected their ability to supply water.

Rainfall

Regions with higher amounts of rainfall showed more sand dams with water, while drier regions had fewer sand dams with water during the assessment. This is expected as water in dams comes from rainwater. Regions with fewer rainfall failures have a higher rate of recharge compared to regions with lower rainfall. It is no wonder developers have put a higher concentration of dams in areas with higher rainfall. 40 sand dams were in the region with the highest amount of rainfall (800–1200 mm), even though this region only covers a small percentage of the land. Sand dams in regions that have more rainfall are likely to serve their intended functions. It could be advisable to avoid the more arid regions. However, equally important is to investigate why several dams found in high rainfall areas were still dry. 14 out of 40 sand dams assessed in the 800–1200 rainfall region did not have any water at the time of the assessment (compare with Gijsbertsen 2007). One of the problems associated with rainfall in arid regions is high spatial variability. It is not known how rainfall variability affects water resources such as sand dams or even whether this variability is seasonal or permanent and the factors that may be contributing to it. In poor and remote regions such as Kitui, installing an adequate gauging network capturing this variability would be difficult and (too) costly.

Some sand dam guidelines recommend that dams should be built in regions with at least 200 mm of rainfall, which may be a rather low number. In Tiva, no sand dams were found in the 200–400 mm ranges, whereas in the 400–600 mm rainfall range, only 2 of 29 dams had water. This implies there may need to raise the bar higher than 400 mm or recommend additional criteria to ensure sand dams will provide water during a drought. Such additional criteria could be developed from studying the 2 sand dams that had water in the 400–600 mm range.

Suitability analyses for subsurface dams based on TWI values and geological data that included stratigraphic information may be applicable (Jamali et al. 2013). Encouraging results were obtained for regions with humid climates and limited natural water storage capacities. In Swaziland, an assessment was done to identify suitable sites for constructing sand dams where high success rates were expected because they were to be constructed in a region with a high (450–600 mm) rainfall amount (Waterpower, 2014). The South African country has a unimodal kind of rainfall, unlike Tiva catchment which is bimodal, which implies this amount of rainfall may have more impact in recharging sand dams and stresses the need for including local factors in any analysis. The unimodal rainfall amount in Swaziland is more evenly distributed compared to Kitui resulting in more ground recharge and, therefore, more sub-surface flow into the sand dams during the drought periods (Andrade et al. 1998).

Vegetation

Tiva's communities knew that presence of Strangler fig (*Ficus thonningii*) and Sycamore fig (Fig-mulberry, *Ficus sycomorus*) indicated an underlying aquifer (see Woodhouse, 1991; Nissen-petersen, 2006). Water indicating tree(s) within 10 m were present at 41 dams, of which 23 (56%) had water. Out of 73 sand dams without water indicating trees, only 23 (31.5%) had water. This supports the use of water indicating vegetation in locating an underlying aquifer. *F. sycamore* tree grows very tall and provide good shade and good stem, unlike *F. thonningii*. As a result, within Tiva catchments, *F. sycamore* is highly sought after for timber, firewood and charcoal making. Therefore, these trees continue to disappear, which brings up the question how many of the water sources cannot be identified today because the trees no longer exist.

There was water indicating trees with signs of water stress, which was taken to imply the aquifer from which they drew water was drying out. If the tree grew for many years before the dam was constructed, that could cause to worry, as in some cases sedimentation in sand dams resulting to clay and silt lenses can cause reduced infiltration (see Wheater and Al-Weshah 2002 and De Trincheria 2016). Under such circumstances, sand dams could actually be counter-productive. There would then need to provide alternatives to recharging such aquifers to ensure continued access to water from such important sources of water in arid environments. Pereira et al (2009) propose recharge wells for riverbeds and subsurface dams that have been rendered impervious.

In case of Tiva catchment, with sand dams built to recharge an underlying aquifer, shallow wells are dug and fitted with pumps. However, of 41 dams with water indicating vegetation, only 18 had hand-dug wells. This may be a critical omission of projects that could deny local people water from such aquifers. On the other hand, it could be expected that community members would sink wells without external support. However, sinking wells is a task only done by men in groups, which requires coordination. This was reported to be difficult. In one case, water indicating tree emerged above a very hard rock that defied all tools at the community disposal. In another village, most of the men were in urban centers searching for paid employment.

Agro-ecological zones

Using agro-ecological zones probably provides the best guide for the likelihood of a sand dam to supply water during dry periods. Use of AEZ maps may provide an important guide for identifying suitable sites for constructing sand dams, as they are readily available from the Kenyan Government institutions. Our analysis shows an increase in the likelihood of a dam to supply water during drought with an increase in the potential for rain-fed agriculture for AEZs defined in 1982 and 2006. Thus, more sand dams could be constructed in LM4 and above, based on the AEZs developed in 2006. For AEZs developed in 1982, regions below a semi-arid zone moisture index of $<40\%$ showed that fewer than 50% of dams had no water, while those in semi-humid or semi-arid zones showed over 50% with water. This is an important observation, as it suggests dams may not be losing more water to evaporation. Beyond a depth of 60 cm below the sand surface, evaporation becomes negligible, which implies that higher temperatures may not lower sand dams' ability to supply water. Thus, sand dams can be an important climate change mitigation technology. Successful dams in lower potential AEZs should be studied thoroughly to ascertain those additional factors that would predict success. In addition, dams without water in AEZs LM4 and above should be studied to ascertain the factors that should be avoided when siting dams.

Stream order

Sand dams built in-stream orders 1–3 showed less likelihood of successfully providing water during drought periods compared to stream orders 4 and 5. Stream order identification may form a useful guide in identifying suitable sites. It is advisable to avoid young rivers when constructing sand dams. Part of the reasons developers avoid building sand dams in high stream orders is the criteria to avoid wide riverbeds due to the high costs involved, criteria that may have contributed to a high number of sand dams in low stream orders and the accompanying inability to supply water during the drought periods. These criteria should be omitted in future guidelines.

Concluding remarks

Projects for improving access to water in the ASAL regions such as Tiva catchment are perceived and expected to be drought relief interventions that would effectively deal with water-related problems. However, quite some interventions have failed to supply water as expected in Tiva, which remains a water-scarce region. Many of the sand dams constructed in Tiva catchment did not increase access to water during drought periods. This could be attributed to poor site identification, as Non-Governmental Organizations (NGOs) and government agencies involved in sand dams' development may lack adequate guidelines for suitable site identification. At the same time, this study has demonstrated that existing criteria for identifying suitable sites for sand dams are insufficient. This suggests that proper site identification is rather complicated, even when strictly adhering to existing criteria. A suitable site requires more than meeting current pre-defined environmental factors and site characteristics. Some of the soil characteristics, topography and geology may not be useful factors at all when identifying suitable sites for constructing sand dams – at least that is what our results from Tiva catchment suggest. Rainfall amount, percentage of clay in soils, presence of rock outcrops, water indicating vegetation, agro-ecological zones and stream orders suggested some degree of predictability for sand dams' ability to supply water in Tiva catchment. However, predictability remained rather low for most of the environmental factors, as some dams did not contain water in regions considered to be most suited. Using AEZs as guidance and stream orders may not provide all the answers to explain sand dam success, but would provide a basis for a more concrete plan that sand dam stakeholders can build on. Factors for success and failure should still be studied and documented, whereas sites where success factors for utilization of sand dams as water resources do not exist in their entity should be avoided.

The assessment we present also provides suggestions for which areas to avoid. Construction of sand dams in regions dominated by vertisols and ferralsols, areas receiving less than 600 mm of rainfall, AEZ of potential below LM4, stream orders 1, 2 and 3, should be avoided, unless more definitive identification criteria are provided. Likewise, dams without water in regions receiving more than 600 mm rainfall or in AEZs over LM4 and stream orders 4 and 5, should be studied to identify which sites to avoid. With this knowledge, suitable sites for construction of sand dams in regions with less than 600 mm, AEZ potential below LM4 and stream orders 1–3 could be identified. These four categories hold the answer to sand dams' inability to supply water during the drought period in Tiva catchment in regions of both high and low potential and develop updated site identification criteria.

Targeted recharge of aquifers should be continued, among others through sand dams or other approaches. It is likely that some aquifers along the riverbeds can benefit from recharging using sand dams, but cannot be identified anymore, for example because water indicating trees have been felled. Past satellite images could be analyzed for such sites. Presence of rock outcrops at a site is not enough to guide to determine whether it would hold water during a drought. A qualified geologist should be called to ascertain whether a site will be permeable. If found to be permeable, sites can either be treated or should be abandoned. In regions where sand dams are found to be inappropriate, other water provision technologies could be identified and implemented.

A map for appropriate implementation of sand dam technology could be prepared for areas like Tiva catchment, using existing data to minimize guess work that may lead to more technology failures and wastage of resources. After all, costs of putting up sand dams that failed are high. With one sand dam costing an estimated USD 5000, in Tiva catchment an estimated USD 132,250 ($23/100 \times 115 \times 5000$) was lost on those dams that supplied water for just one week which can be considered as a complete failure. Alternative technologies, such as plastic-lined ponds or tanks, could have resulted in more access to water for communities. Plastic-lined ponds are cheap, but can only target individual farmers while water tanks can target schools and larger households. The challenge with these other technologies is that they do not readily render themselves for communal water access. Sand dams have probably gained popularity because they do build on community efforts, which is why sand dams may continue to be one of the more useful technologies to provide rural communities with adequate water, now and in future.

Concerning this future, our study suggests that increases in temperature through climate change would not necessarily adversely increase evaporation from sand dams nor effect their success. In regions where sand dams successfully supply water during the drought period, they could be an important climate change mitigation technology. Constructing those dams, however, should not be based on simple criteria that are applied without studying the environmental conditions in the depth that is required. There is a need to go back to the drawing board for sand dams to become the universally successful climate-mitigation technology that so many think they already are.

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