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Investigating the environmental response to water harvesting structures: A field study in Tanzania

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Abstract. Sand dams, a popular water harvesting structure employed by rural communities, capture and store water for use during the dry season in arid and semi-arid regions. Most sand dam research has been performed on the "ideal" sand dam, despite approximately fifty percent of sand dams not functioning as intended. This research involves a year-long, in-depth field study of three sand dams in Tanzania, one of which is essentially non-functioning. The study investigated a sand dam's impact on macroinvertebrate habitat, vegetation, streambank erosion, and the local water table. Surveys of macroinvertebrate assemblage were performed each season. Vegetation surveys were performed every other month, and erosion was recorded semi-monthly. Water table monitoring wells were installed at each sand dam, and measurements were taken twice a day. The study showed that sand dams are not a suitable habitat for macroinvertebrates. The non-functioning sand dam has a thick layer of silt preventing infiltration of rainwater. The functioning sand dams store a significant amount of water, but most is lost to evapotranspiration within a few months of the last rainfall. Unlike the non-functioning sand dam, the functioning sand dams have a positive impact on local vegetation and minimal impact on erosion. Sand dams can increase the water security of a community, but site characteristics and construction methods must be strongly considered to maximize the sand dam's positive impact.

1 Introduction

International development projects in the Global South are managed by either a national department, private company, non-governmental organization (NGO), or a group of international development agencies (Ika, 2012). Success metrics for international development projects are typically defined by the funding organization, which are most often multilateral or bilateral organizations (e.g. the World Bank, United States Agency for International Development, etc.) or individual donors (Ika, 2012). Unfortunately, project success metrics frequently only tell one side of the story, focusing on financial and technical management rather than the social, cultural, and environmental impacts (Ika, 2012; Julian, 2016). Such a narrow definition of success omits both positive and negative unexpected consequences of international development work (Julian, 2016). Underreporting of project outcomes results in an inadequate understanding of the impact of international development work. Failure to consider whether intended long-term goals are met wastes time, money, and resources.

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One example of international development projects with a questionable record of success are water harvesting structures in sub-Saharan Africa. When a specific technology's ability to improve water security is not honestly communicated along with the technology's other long-term impacts, outside organizations may embrace the technology without understanding the associated risks. Misunderstood risks lead to situations where a water harvesting technology proliferates without consideration of project pitfalls. This has been the case with sand dams in sub-Saharan Africa. Sub-Saharan Africa is home to over 1500 sand dams (de Trincheria et al., 2015), yet approximately 50 % of sand dams are essentially non-functioning (Viducich, 2015).

Most information about sand dams comes from NGOs painting a rosy picture of the innumerable positive impacts of sand dams. Other information on sand dams comes from studies published on one or two ideal sand dams or from sand dam models. One in-depth sand dam study examined the hydrology of a Kenyan sand dam and performed a water balance assessment of the sand dam (Borst and de Haas, 2006). Results from this study were used to develop a couple of sand dam models that explored how sand dams impact the local water table (Hoogmoed, 2007; Quilis et al., 2009). Other studies used modelling to further explore the seepage of sand dam water through streambanks (Hut et al., 2008) and the potential of sand dams to increase water security in Ethiopia (Lasage et al., 2015). The socio-economic benefits of sand dams has also been explored (Lasage et al., 2008) along with the negative effects of sand dam siltation and/or seepage due to poor construction and or siting (Nissen-Petersen, 2006; de Trincheria et al., 2015; Viducich, 2015). Except for the Borst and de Haas (2006) study on the ideal sand dam, most published sand dam studies are based on survey data or modelling efforts. Published studies do not tell the whole story of sand dam impacts, and this has created a false perception of the risks involved with sand dam construction.

This study aims to respond to anecdotes with science and seeks to discover how diverse sand dams influence macroinvertebrate habitat, vegetation, erosion, and groundwater recharge in the riparian zone. Specifically, the study will answer the following questions: (1) Are sand dams able to support macroinvertebrates? (2) What factors determine a sand dam's impact on vegetative growth? (3) How is streambank erosion affected by sand dams? (4) How do sand dams alter the groundwater table in the surrounding area? These questions will be answered through an in-depth field study of three sand dams in Tanzania. The sand dams are selected based on community interest in the study and diversity of dam features, such as stream width, dam effectiveness, stream valley slope, and local vegetation. This diversity of features ensures that the sand dams included will be representative of the sand dams found throughout the region, and this study will therefore create a holistic understanding of how a sand dam interacts with the local environment.

2 Study Area

Tanzania is home to 55.5 million people, 70 % of whom reside in rural areas (United Republic of Tanzania National Bureau of Statistics, 2015). The climate of Tanzania varies regionally, but most of the country experiences a tropical savannah or a warm semi-arid climate (Peel et al., 2007). The northern part of the country experiences annual bimodal rainfall, with rainy

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seasons occurring March to May and October to December. The central and southern part of the country experiences annual unimodal rainfall, with the rainy season occurring from October to April (see Fig. 1a; Luhunga and Djolov, 2017). Tanzania is fairly flat, with the exception of the highlands on the southern border and, of course, Mount Kilimanjaro to the east of Arusha. There are at least 15 sand dams in Tanzania, three of which will serve as study sites for this research (see Fig. 1a). Most of the sand dams were funded by the Mennonite Central Committee of Tanzania (MCC) and designed by Kenya-based non-governmental organizations. Dodoma has nine sand dams; Longido, a small town near the Kimokouwa sand dam (see Fig. 1a), has four sand dams, and there are a few sand dams elsewhere in the country.

The sand dams selected for inclusion in this study all have an active community water group that was willing and able to participate in the study. The community water groups have formal ownership of the land surrounding the sand dams, and the research activities were generally limited to this land. One of the sand dams selected, Kimokouwa, was known to store very little water outside of a few days after a rain event. The other two sand dams, Soweto and Chididimo, store water for a couple of months into the dry season. The Soweto and Chididimo sites have different site geology, and therefore provide different insights into the potential of sand dams to impact their local environment. All three sand dams vary in their construction specifications (see Table 1). The width of the spillway is essentially equal to the width of the stream at each site.

2.1 Kimokouwa sand dam

The Kimokouwa sand dam (see Fig. 1b) is located approximately 11.5 km south of the Kenya border. Construction of the sand dam was completed in November 2011 with funding provided by MCC and design and construction expertise provided by the Utooni Development Organization of Kenya. A hand pump was installed near the sand dam in April 2016. MCC requested this site be included in the study, because the sand dam proved ineffective at capturing and storing water for the community's use. MCC hoped that the research could help identify the factors contributing to the sand dam's failings and inform their future work.

2.2 Soweto sand dam

The Soweto sand dam (see Fig. 1c) is located approximately 20 km west of Dodoma, Tanzania's capital city. Construction of the sand dam was completed in June 2011 with funding provided by MCC and design and construction expertise provided by the Sahelian Solutions Foundation of Kenya. A hand pump was installed near the sand dam at the time of dam construction. The Soweto site is the flattest of the three sand dam sites, with an elevation change of only 14 m across the site. The streambanks are quite flat near the dam, and the community is able to grow many crops on the banks, using water from the sand dam to irrigate the crops. At 17 m wide, the stream at Soweto is also the widest of the three sand dam sites.

2.3 Chididimo sand dam

The Chididimo sand dam (see Fig. 1d) is located approximately 3.2 km south of the Soweto sand dam. Construction of the sand dam was completed in June 2011 with funding provided by MCC and design and construction expertise provided by the Sahelian Solutions Foundation of Kenya. A hand pump was installed 180 m upstream of the sand dam at the time of dam construction. The Chididimo sand dam is constructed in a fairly uniform stream valley, with relatively steep slopes covered with long grasses and large trees. The abundant vegetation is expected to reduce erosion at the site, but the steep stream valley likely means that the sand dam will have a less pronounced impact on the local water table.

3 Data Collection and Analysis

3.1 Community water groups

Each sand dam selected for this study has an active, officially registered, community water group responsible for managing the sand dam. The community water groups were involved in the field work for this study from the first day. In addition to meeting with the researchers regularly, each group provided three to six volunteers to take twice daily and bi-weekly measurements. The volunteers were trained in proper data collection and recording procedures and were provided all materials necessary to complete the work.

3.2 Macroinvertebrate survey

Macroinvertebrate surveys performed at each site were intended to serve as an indication of water quality and overall habitat health. At each sand dam, samples were extracted at two locations upstream of the dam and one location downstream of the dam. All samples were taken from the middle of the streambed. During the dry season, a 25 cm x 25 cm by 10 cm-deep hole was dug in the streambed with a small shovel, and the extracted bed material was transferred to a plastic bucket (Verdonschot et al., 2014). Holes drilled in the bucket's lid were plugged with cotton to prevent transfer of macroinvertebrates into or out of the sample (Stubbington et al., 2009). The samples were transported to the research base and rehydrated with de-chlorinated water to encourage re-emergence of desiccation-tolerant life stages (Boulton et al., 1992; Stubbington et al., 2009). For a 28 day period, the samples were checked daily for macroinvertebrates. During the wet season and at the start of the dry season when the streambed was still fairly wet, a 25 cm x 25 cm by 10 cm-deep hole was dug in the streambed with a small shovel, and the extracted bed material was sieved through a 2 mm mesh sieve at the site. Any macroinvertebrates found would have been stored in a 10 % formaldehyde solution for later identification (Stubbington et al., 2009).

3.3 Vegetation survey

Vegetation surveys were performed approximately every two months to capture the seasonal change in vegetative cover near the sand dams. The surveys were done in accordance with the line intercept method (Lutes et al., 2006). At each site, four 20 m-long transects were laid perpendicular to the stream flow and marked with wooden stakes. One transect was sampled downstream of each sand dam and three transects were sampled upstream of each dam with a 50 cm x 50 cm quadrat (Lutes et al., 2006). During each survey, the quadrat was placed consecutively along the transect, and the percent of vegetative cover was estimated visually (Lutes et al., 2006; Mallik and Richardson, 2008). At Soweto and Chididimo, quadrat 1 was placed at the stream edge and the transect extended away from the stream. Two transects were laid on the left-hand side of the stream, and two were laid on the right (see Fig. 1 b,c). At Kimokouwa, where the stream is narrow, the centre of each transect lay at the middle of the stream (see Fig. 1d).

3.4 Erosion study

Erosion pins were installed at each site to track the amount of streambank erosion occurring upstream and downstream of the sand dams. Welding rods 300 mm in length and 4 mm in diameter were used as erosion pins when the bank material was soft enough to insert the rods without deforming them (Lawler et al., 1999; Saynor and Erskine, 2006). The welding rods were painted to prevent rusting (Saynor and Erskine, 2006). Stainless steel rods 300 mm in length and 6 mm in diameter were used as erosion pins elsewhere (Stott, 1997). The pins were inserted into the streambank leaving 75 mm of the pin exposed at a vertical spacing of ¼, ½, and ¾ of the bank height and at a horizontal spacing of one meter (Palmer et al., 2014). At Kimokouwa and Soweto, erosion pins were placed at two locations upstream of the dam and one location downstream of the dam. At Chididimo, pins were placed at one location upstream of the dam (see Table 2). Fewer pins were installed at Chididimo, because the stream did not have a clearly defined bank, and, where present, the streambank was often too rocky to permit insertion of the pins.

Volunteers from the community water groups took erosion measurements approximately every two weeks using a 150 mm rule depth gage. The length of pin exposed was recorded to the nearest mm for each pin. If more than 100 mm of the pin was exposed, the pin was reset so only 75 mm was exposed. In the event that the pin was missing due to extraordinary erosion, the researchers assumed that 240 mm, or 80 % of the pin's length, of erosion occurred at the pin's location (Palmer et al., 2014). When a pin could not be found and appeared to be buried in the streambank due to a large deposition event, a new pin was installed with 75 mm exposed.

3.5 Water table monitoring

Water table monitoring wells (WTMW) were installed at each sand dam to track changes in the water table over time. A drilling team hand-augured boreholes 10 cm in diameter at 63 locations across the three sites (see Table 3). For each WTMW, the drilling team continued drilling until the team encountered hard rock or another material prohibiting the progress of the auger. A WTMW was installed only if a hole deeper than 0.5 m was achieved. A soil log was completed for each WTMW noting the soil depth, texture, colour, wetness, and cohesion for each horizon. See Fig. 1b-d for WTMW layout at the sand dams. Figure 2 provides a schematic of the WTMWs. The WTMWs installed were schedule 40 polyvinyl chloride pipe 32 mm in diameter. To create a well screen, four 6.35 mm holes were drilled around the circumference of the pipe every 2.5 cm, leaving the top 60 cm of the pipe undrilled (Sprecher, 2008). Geotextile filter fabric was unavailable, so the well screen was covered with women's hosiery instead (Borst and de Haas, 2006). The well caps at the top and bottom of the WTMWs were vented to prevent pressure from building up inside the pipe resulting in incorrect measurements. At the ground surface, a mounded concrete pad was built to secure the WTMW in place and to encourage rainfall to drain away from the structure (see Fig. 2).

Volunteers from the community water groups took measurements of the water table every morning and evening during the rainy season after the WTMWs were installed. After the wells dried up, measurements were taken less frequently—approximately once a week. The water table measurements were taken by slowly lowering a Solinst® Model 101B Basic Water Level Meter into the WTMW until the buzzer was activated indicating water had been reached. At this point, the distance from the top of the WTMW pipe to the sensor was recorded to the nearest cm in a notebook along with the date and time of day.

At Kimokouwa, the community water group volunteers took measurements of the water depth for a few weeks after the WTMWs were installed, but water was only detected in the well closest to the sand dam up to two days following even a large rainfall event. The sand dam was clearly not storing much water. The volunteers and the researchers agreed to cease WTMW measurements at Kimokouwa so as to not waste the volunteers' time. At Soweto, the frequency and regularity of the WTMW measurements varied somewhat, with the measurements being more consistent later in the project timeline. The Chididimo community water group volunteers were very dedicated to the task of recording water table depths every morning and evening. Of the three sand dams studied, the Chididimo data provides the best picture of how the water table fluctuates near a sand dam.

The water table measurements were used to determine the volume of water in the sand dam over time. To define the cause of water loss from the sand dam, a water balance was calculated using remote sensing data from Famine Early Warning Systems Network Land Data Assimilation System (FLDAS). The theoretical water loss from the sand dam is:

$$Q_{out}(t) = 0.038 \times C \times P(t) - 0.85 \times E(t) - Q_{sb}(t) - Q_{com}(t) \,, \quad (1)$$

where Q_{out} is the water loss from the sand dam, C is the runoff coefficient used in the rational method, P is rainfall, E is total evapotranspiration, Q_{sb} is baseflow-groundwater runoff, and Q_{com} is the community's water use. The runoff coefficient selected is 0.26, because the soil is mostly open sandy loam in Dodoma, and the land near the sand dams is a cross between pasture and woodland (Indiana, 2013). Runoff, $C \times P(t)$, is multiplied by a factor of 0.038, because Aerts et al. (2007) found that sand dams in Kenya store a maximum of 3.8 % of the total runoff. Total evapotranspiration, E, is the sum of canopy-intercepted evaporation, transpiration from vegetation canopies, and evaporation from bare soil (McNally et al., 2017). A sand dam will not lose water due to evaporation of canopy-intercepted rainfall, so including this portion of E in the water balance is inappropriate. Kumar et al. (2018) found that canopy-intercepted evaporation accounts for approximately 15 % of the total evapotranspiration simulated in the Noah Land Surface Models, which are incorporated into FLDAS (McNally et al., 2017). Therefore, total evapotranspiration is reduced by 15 % in Eq. (1). The community's water use was calculated using estimates provided by the community water groups.

4 Sand dam impact

4.1 Macroinvertebrates

The various macroinvertebrate survey trials produced only one specimen—at Kimokouwa during the dry season. This failure to produce macroinvertebrates indicates that sand dams are not a suitable habitat for macroinvertebrates during any season of the year. Duan et al. (2008) found that sandy substrate is the least suitable for macroinvertebrates and produces the lowest taxa richness of all substrates studied. This is partly due to benthic fauna being unsuited to sandy substrates, causing them to be fairly homogeneous (Duan et al., 2008). Sandy substrate also has small interstice dimensions that provide only very small living spaces for macroinvertebrates (Duan et al., 2008). Homogeneous bed material suggests that there are few, or no, structures available for macroinvertebrates to use as refugia during high streamflow (Taniguchi and Tokeshi, 2004). In addition to providing refugia, a heterogeneous habitat offers myriad niches for different species to utilize during various stages of their life cycle (Salant et al., 2012). Furthermore, macroinvertebrates feed on bacteria, algae, and other organic matter, which may be scarce in sandy substrate (Taniguchi and Tokeshi, 2004).

In the case of the sand dams studied, there were very few plants, cobbles, or larger rocks present in the stream channel. The sand within the sand dam, with the exception of Kimokouwa, was largely a mixture of fine- and coarse-grained sand, as one might expect to see at a beach. This environment precluded macroinvertebrates from inhabiting the sand dam. Macroinvertebrates are often used as an indicator of water quality, but the lack of macroinvertebrates in the sand dams here should not be assumed to signify the water was of low quality. The aforementioned compounding factors likely largely explain the absence of macroinvertebrates in the sand dams.

4.2 Vegetation

The vegetative cover at the three sand dams differed greatly throughout the study (see Fig. 3). Kimokouwa, unsurprisingly, had the lowest level of vegetative cover overall and did not see much increase in vegetative cover during the rainy season. Soweto, the flattest site, showed the greatest improvement in vegetative cover between the dry season and the rainy season. Each Soweto transect exhibits a significant increase in vegetation. Interestingly, Chididimo only had significantly more vegetation at the two transects farthest upstream from the sand dam (VT3 and VT4). The slope of the Chididimo stream valley became gentler farther upstream of the dam, which created favourable conditions for increased vegetation during the rainy season. Of the three sand dams, Chididimo has the highest level of vegetation during the dry season, and therefore had the least opportunity for significant increases in vegetation during the rainy season.

As suggested by Fig. 3, the average percent vegetative cover at a sand dam is correlated to the land slope near the sand dam. As the elevation above the streambed increases, the percent vegetative cover generally decreases during both the rainy season and the dry season (see Fig. 4a). The trend of decreasing vegetative cover as elevation above the streambed increases is more consistent during the dry season but is also evident during the rainy season. Two conditions combine to create the trend seen in Fig. 4a. Lower elevation above the streambed gives rise to (1) groundwater seepage through the streambanks being closer to the land surface, and/or (2) a gentler slope giving rainwater more time to infiltrate into the soil, because overland flow travels slower over a gentle slope. The conditions support vegetative growth, because more soil water is available for plant uptake. As Fig. 4a indicates, there is low vegetative cover right at the stream edge (lowest elevation), which signifies streamflow frequently rising above this point.

The upstream and downstream trends differ at the three sand dams. At each sand dam, there is more vegetation upstream of the sand dam than downstream (see Fig. 4b). However, this difference is most significant at Soweto, where the change in elevation across the site is small relative to the Kimokouwa and Chididimo sand dams. Of the three sand dams studied, only the sand dam located in a flat area exhibited a large increase in vegetation upstream of dam, indicating that a sand dam's impact on vegetation may be limited by the slope of the surrounding land. Also, the rate of vegetative cover at the two functioning sand dams, Chididimo and Soweto, is high compared to the non-functioning Kimokouwa sand dam. A functioning sand dam is able support more vegetation, because of the additional stored water that is available to vegetation for use in transpiration.

4.3 Streambank erosion

The temporal changes in the bank soil varied somewhat across the three sand dams (see Fig. 5). Kimokouwa and Soweto exhibited little change in bank volume at the upstream location, and Chididimo experienced a high rate of soil deposition. Interestingly, bank erosion increased at Kimokouwa during the rainy season, while bank deposition increased at Chididimo during the rainy season. The differences in bank morphology and floodplain vegetation between the two sites impact their respective erosion/deposition dynamics. At the downstream locations, Soweto did not exhibit much change in bank soil, while the Kimokouwa site showed severe erosion, particularly during the long rains season (mid-February to April). The Kimokouwa downstream bank lost a total of 40 mm of soil throughout the course of the study due to mass bank failure. The heavy rainfall during the long rains season led to a pre-wetted bank with heightened pore water pressures. Eventually, the pore water pressures exceeded the structural integrity of the bank, and the bank material fell into the stream channel in large volumes (Hooke, 1979; Lawler et al., 1999). The downstream Kimokouwa bank experienced multiple mass failures throughout the long rains season (see Fig. 5).

The spatial changes in bank soil also vary between the three sand dam sites (see Fig. 6). The Kimokouwa streambanks exhibit a consistently high rate of erosion across the entire bank height. The high rate of erosion is likely due to the relatively steep and/or vertical banks and minimal vegetative cover. At Chididimo, the streambank generally experiences deposition across the bank height, but does experience lower rates of deposition at the foot of the bank with some periods of erosion occurring. This is clear from the high standard error for ¼ bank height at Chididimo. Erosion at the foot of the Chididimo streambank is caused by high streamflow during the rainy seasons. At Soweto, soil eroded from the top of the bank is deposited at the middle and foot of the bank. However, the extremely long standard error bars for Soweto erosion measurements at all bank heights challenge the validity of the Soweto erosion data. The community volunteers at Soweto may have been erroneously recording the erosion measurements, despite repeated training and practice sessions with the primary field researcher. The Soweto erosion data should be considered sceptically. However, based on Soweto erosion data taken solely by the primary field researcher, the overall trend of little erosion and deposition occurring at Soweto can be confirmed.

The Kimokouwa sand dam was constructed in an unstable reach. The stream channel is actively migrating, which causes the stream to flow into the left wing wall of the sand dam, rather than flow over the spillway. A strong eddy develops, eroding the soil directly behind the dam. Water fills the large hole created by the erosion, and silt settles onto the dam surface, acting as a capillary barrier. The erosion of the soil behind the dam threatens the stability of the dam, because the dam's design depends on the weight of the soil to help hold the dam in place. That the stream channel is migrating likely contributes to the mass erosion of the bank downstream of the sand dam (see Fig. 5).

4.4 Water Table

The sand dam at Kimokouwa is unable to store much water, due to a 1.2 m thick silt layer beginning at a depth of 0.5 m that acts as a capillary barrier. The rest of the sand dam has smaller silt layers interspersed between layers of silty sand. The silt layer prevents water from infiltrating deep into the sand dam and prevents the free flow of water to the hand pump near the sand dam. As a result, the community is unable to use the sand dam as a source of domestic water. Silt layers formed at the Kimokouwa sand dam, because the dam was improperly constructed for the type of soil present in the area (Nissen-Petersen, 2006; de Trincheria et al., 2015). Siltation of a sand dam occurs during rainfall events prior to the sand dam's maturation, or before the sand reservoir has naturally reached the height of the spillway. Sand dams in areas with silty sand should be constructed in thirty cm stages to ensure that the portion of the water column with suspended silt flows over the spillway instead of settling behind an immature sand dam (Nissen-Petersen, 2006).

A functioning sand dam typically fills with water after one high intensity rainfall event and remains essentially full throughout the rainy season (Ertsen and Hut, 2009). The stored water seeps into the banks, raising the water table in the riparian zone. The last rainfall of the season at Chididimo and Soweto occurred in the middle of April, approximately the sixteenth week of the year. Fig. 7a shows that within just ten weeks of the last rainfall, the Chididimo sand dam had dried significantly, leaving very little abstractable water available to the community. The Soweto sand dam has a much greater storage capacity, and retains abstractable water for approximately fifteen weeks after the last rainfall (Fig. 7b). Soweto's greater storage is due to the wider and deeper sand reservoir. The sand dams at Chididimo and Soweto only store water for community use during the first few months of the dry season.

In Chididimo, there are three sources of water: the sand dam and two boreholes drilled by an international non-profit organization. When there is water in the sand dam, the community draws all water for agricultural use from the dam and about half of the domestic water from the dam, totalling 15 000 litres of water per week (Chijendelele na Mlimo Group, personal communication, May 30, 2017). However, their total water use accounts for only about 5 % of the water stored by the sand dam at peak volume. Unsurprisingly, most of the water in the sand dam is lost to evapotranspiration. With only 1 % of the total water lost attributed to baseflow-groundwater runoff and 9% unaccounted, evapotranspiration was responsible for 85 % of the water lost from the Chididimo sand dam according to FLDAS data and Eq. (1) (see Fig. 7a). The unaccounted water loss could be due to seepage or possibly a higher rate of evapotranspiration than simulated by FLDAS.

In Soweto, the sand dam is the only nearby source of water. When the sand dam is dry, community members must travel seven km to draw water from a well in a nearby village. When able, the community draws approximately 39 000 litres of water from the sand dam per week for both agricultural and domestic use (Vumilia Group, personal communication, June 1, 2017). Their total water use accounts for only about 8 % of the water stored by the sand dam at peak volume. With only 1 % of the total water lost attributed to baseflow-groundwater runoff and 40 % unaccounted, evapotranspiration was responsible for 51 % of the water lost from the Soweto sand dam according to Eq. (1) (see Fig. 7b). Like Chididimo, the unaccounted water loss could be due to seepage or possibly a higher rate of evapotranspiration than simulated by FLDAS.

Figure 7 shows that the sand dams lost water at a slower rate than predicted by Eq. (1) during the rainy season and a faster rate after the rainy season ends. The nearly constant decrease in water volume after the end of the rainy season indicates that the water is likely being lost due to evapotranspiration. The decreasing volume of water in the dam means that the pressure head driving any seepage under the dam is also continuously decreasing, reducing the rate of seepage. Therefore, seepage cannot be the primary cause of the constant, high rate of water loss during the dry season.

Evapotranspiration is occurring during the dry season at a faster rate than simulated by FLDAS. The FLDAS dataset calculates evaporation from bare soil based on simulated soil moisture content (McNally et al., 2017). However, the dataset does not account for water available in the sub-surface water reservoir created by the sand dam. The line fit to the field data after the end of the rainy season indicates that the Chididimo and Soweto sand dams are losing water primarily via evapotranspiration at a nearly constant rate of 400 000 and 110 000 L week^{-1}, respectively. This high rate of evapotranspiration means that the sand dams can no longer provide water to the community after the months of July or August in most years.

The Soweto sand dam is losing water during the dry season at nearly three times the rate of the Chididimo sand dam. The width of the Soweto sand dam is nearly twice that of Chididimo, providing more surface area for evaporation to occur (see Table 1). Also, different types of vegetation transpire water at different rates (Lautz, 2008). The banks of Chididimo are generally covered with natural vegetation, whereas the Soweto community intensively cultivates the banks. Natural vegetation in a semi-arid climate requires less water than cultivated crops, therefore the rate at which the Soweto vegetation transpires water contributes to Soweto's rapid water loss. Seepage under the dam is also likely an issue at the Soweto sand dam. At Soweto, community members often dig scoopholes just downstream of the dam, indicating that there was a substantial, steady supply of water seeping underneath the dam. The combination of stream width, vegetative cover, and seepage contribute to Soweto's higher rate of water loss.

One of the most common reasons given for building sand dams is that they provide water to communities throughout the dry season. At Chididimo and Soweto, this is simply not the case. Chididimo and Soweto experience approximately 100 mm lower annual rainfall and higher rates of evapotranspiration than a typical sand dam in Kenya experiences (NASA/GSFC/HSL, 2016). Sand dams are intended to protect the stored water from evaporation, but the ground surface is inadequate protection against the high temperatures and dry air at the Chididimo and Soweto sand dams.

5 Discussion of impacts and recommendations

The impact of a sand dam depends not only on its dimensions and construction but also on features of the surrounding land and the management of the dam's water resource by the local community. The field study revealed that a non-functioning sand dam might significantly influence streambank erosion but has little impact on the local water table and vegetation. The functioning sand dams, however, had little impact on streambank erosion, significant impact on the local water table, and varied impact on vegetation. Regardless of a sand dam's functionality, none of the sand dams in the study were a suitable habitat for macroinvertebrates. The absence of macroinvertebrates in sand dams may cause a loss in the value of ecosystem services, such as nutrient cycling, decomposition of organic matter, or primary productivity. The loss of these services, however, may be outweighed by the increased water security.

The two functioning sand dams support more vegetation than the non-functioning sand dam. The increase in vegetation caused by the sand dam's additional stored water is much more apparent when the surrounding land is relatively flat (i.e. at Soweto). A locally raised water table in a flat area results in soil water that is closer to the land surface than if the sand dam were surrounded by steep slopes, like at Chididimo. The increased soil water close to the land surface is available to support vegetative growth and results in higher vegetative cover. Therefore, to maximize the positive impact of a sand dam on local vegetation, sand dams should be built in flat areas.

The two functioning sand dams have fairly stable streambanks compared to the non-functioning Kimokouwa sand dam. The streambanks at Kimokouwa exhibit fairly severe erosion, particularly at the site downstream of the sand dam. The Kimokouwa sand dam was constructed between two fairly sharp bends in the stream, and the flow of water over the sand dam adds energy to the water in the stream. With this added energy, the water erodes more of the streambanks and is likely contributing to the migrating of the Kimokouwa stream channel. Sand dams should therefore be built in stable, straight reaches to minimize the chance that the construction of a sand dam will negatively impact the course of the stream.

While the non-functioning Kimokouwa sand dam does not increase the availability of water in the local community, the functioning sand dams provide a local water resource for at least the first few months of the dry season. However, the two functioning Dodoma sand dams do not store water throughout the entire dry season, as is an often stated benefit of sand dams. Dodoma lies in the unimodal rainfall region of Tanzania, whereas Kenyan sand dams experience bimodal rainfall. With only one period of rainfall every year, the Dodoma sand dams are unable to supply water throughout the eight-month dry season. In addition, the Dodoma sand dams receive approximately 100 fewer mm of rainfall every year and average higher rates of evapotranspiration than the annual rainfall and average evapotranspiration at the Kenyan sand dams. Less rainfall and higher evapotranspiration result in sand dams that function at a lower level than those in Kenya.

A frequently cited benefit of sand dams is that they protect the stored water from evapotranspiration. While the sand dams help slow the rate of evapotranspiration, evapotranspiration is still the greatest loss factor for the stored water. Chididimo has a shallower sand dam and lost at least 85 % of its stored water to evapotranspiration, while Soweto is deeper and lost at least 51 % of its stored water to evapotranspiration. However, the 9 % and 40 % unaccounted loss at Chididimo and Soweto, respectively, was likely lost primarily via evapotranspiration. Typically up to 65 % of rainfall is lost to evapotranspiration (Trenberth et al., 2007), but the evapotranspiration losses at the two sand dams significantly exceeded this rate. The deeper Soweto sand dam lost less water to evapotranspiration than the shallower Chididimo sand dam, because the rate at which sub-surface water can be evaporated depends, in part, on the depth of the water below the ground surface (Hellwig, 1973). To help reduce the amount of water lost from sand dams due to evapotranspiration, sand dams should be constructed in locations where a deep sand reservoir can develop.

6 Conclusions

An in-depth field study of three diverse sand dams was performed to develop a comprehensive understanding of how the sand dams interact with their local environment and to assess their impact on the availability of water to the community. The study revealed that sand dams are not an appropriate habitat for macroinvertebrates, largely due to their homogeneity. Overall, functioning sand dams support increased vegetative growth, but the improvement is limited by the land slope. Sand dams have a varied impact on streambank erosion. The downstream bank at the non-functioning sand dam exhibited severe erosion, while deposition and/or little change was largely observed at the two functioning sand dams. Finally, functioning sand dams have a positive, but evaporation-limited, impact on the local water table. Many factors influence the functionality of sand dams and should be considered when planning for new sand dams. Per the study findings, sand dams should be constructed in a flat area, and it is imperative that they are constructed in a stable stream. Despite a design intended to reduce evapotranspiration losses, sand dams still experience a high rate of evapotranspiration. Clever solutions for mitigating evapotranspiration losses might be the key to unleashing the potential of sand dams. Future work based on this study will focus on developing improved guidelines for siting new sand dams.

Data Availability

The raw sand dam data has been published in the Purdue University Research Repository and can be accessed at: https://www.doi.org/10.4231/GYSC-1X41 (Eisma and Merwade, 2019). FLDAS data can be downloaded at: https://disc.gsfc.nasa.gov/datasets?Keywords=FLDAS.

Author contribution

Jessica Eisma collected and analysed data during the field studies and prepared the manuscript. Venkatesh Merwade supervised the data analysis and contributed to the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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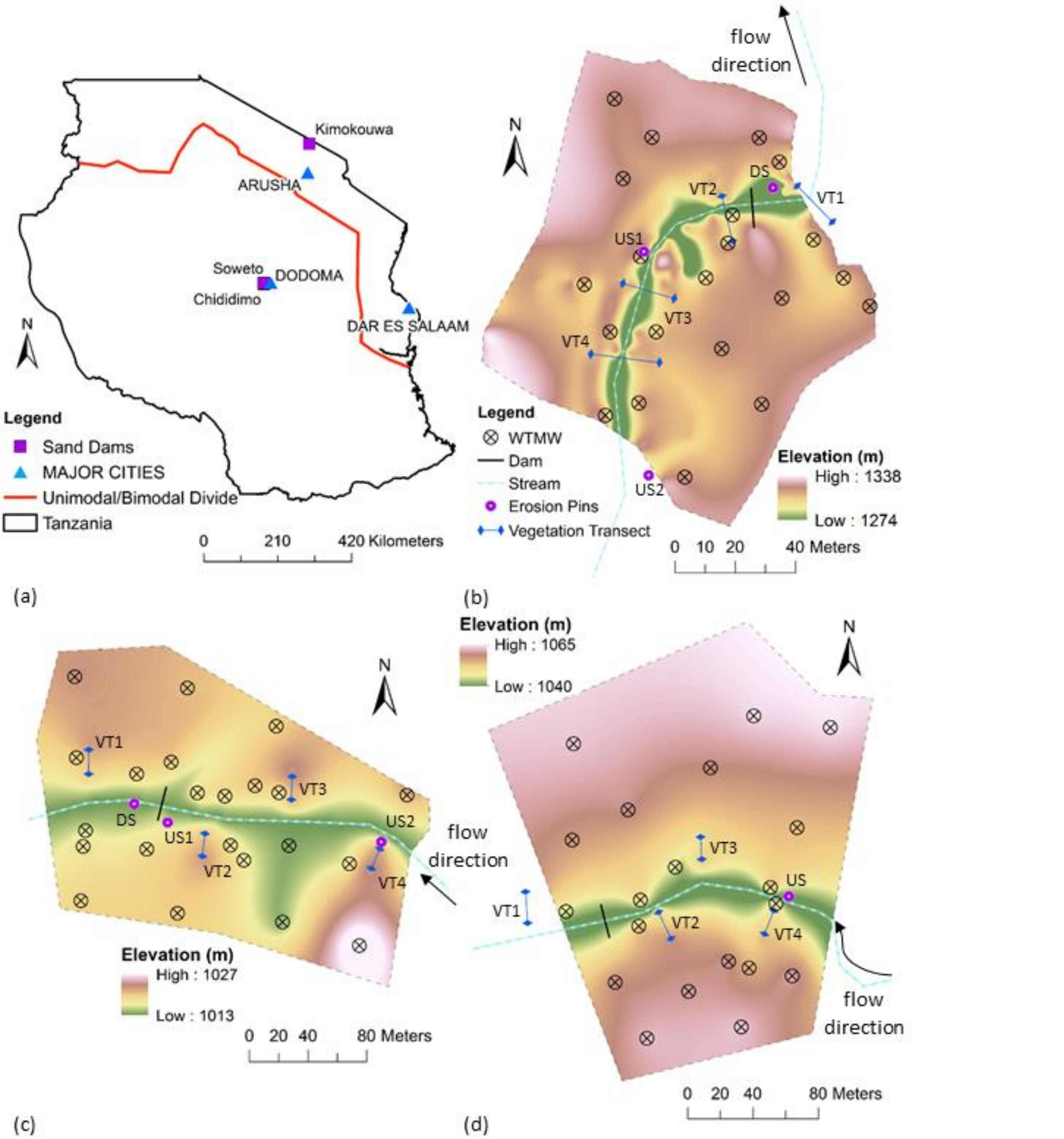

Figure 1: (a) Study Area. The bimodal rainfall region is north of the red line; the unimodal rainfall region is south of the red line (Luhunga and Djolov, 2017); (b) Kimokouwa study area; (c) Soweto study area; (d) Chididimo study area. Elevations are interpolated from GPS points taken during study. The elevation map includes only the area controlled by the community water groups.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-147
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 26 April 2019

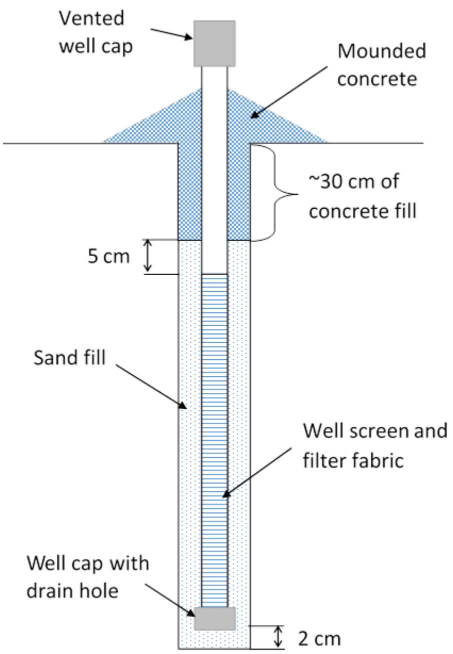

Figure 2: Schematic of the water table monitoring wells installed (adapted from Sprecher, 2008).

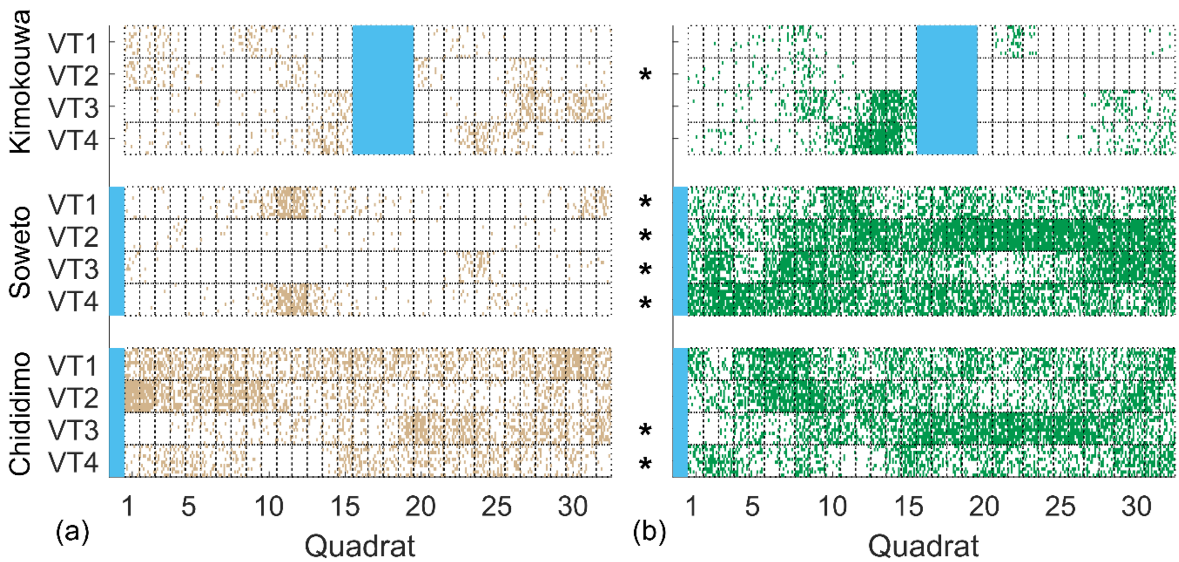

Figure 3: Representation of percent vegetative cover for each transect at each sand dam during the (a) dry season and (b) rainy season. The stars indicate a significant difference (p<0.05) between the wet and dry season vegetative cover for that transect. The solid colour indicates the location of the stream relative to the transect. VT1 is downstream of the dam; VT2–4 are upstream.

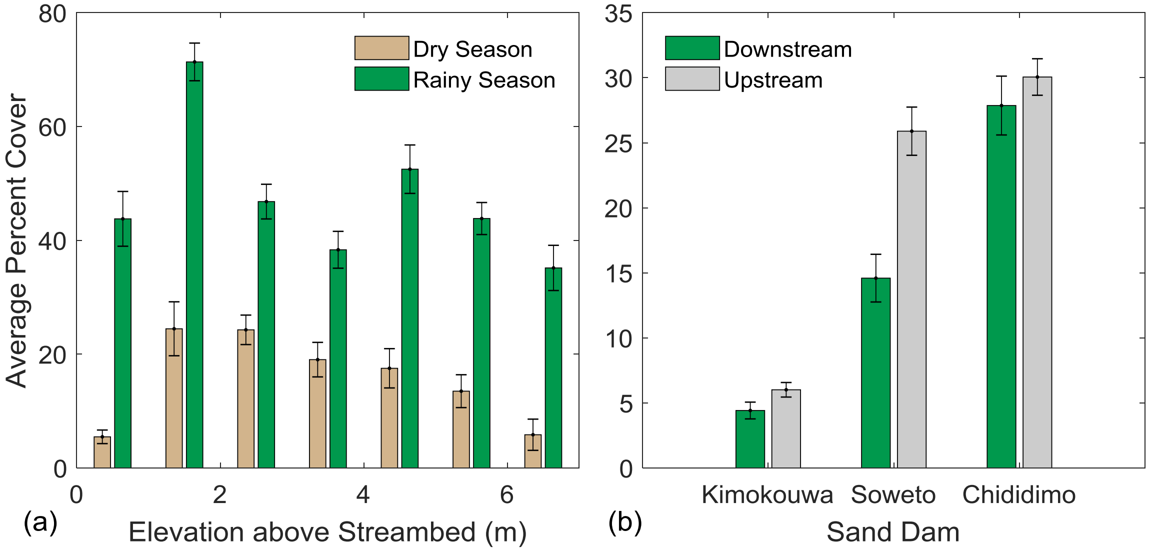

Figure 4: (a) Average percent cover at different elevations above the streambed for the dry and rainy seasons at the Soweto and Chididimo dams. Kimokouwa sand dam was excluded, because the sand dam is not functioning. Standard error bars are shown; (b) Average upstream and downstream vegetative cover at the three sand dams. Standard error bars are shown.

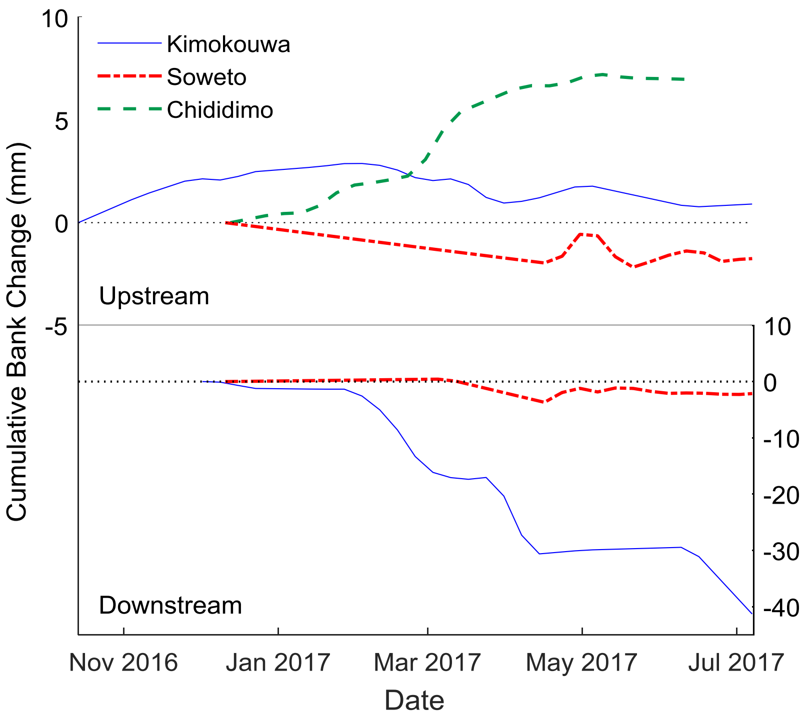

Figure 5: Cumulative bank change over the duration of measurement at each sand dam for the upstream and downstream pinned banks. A positive value signifies deposition, a negative value indicates erosion.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-147
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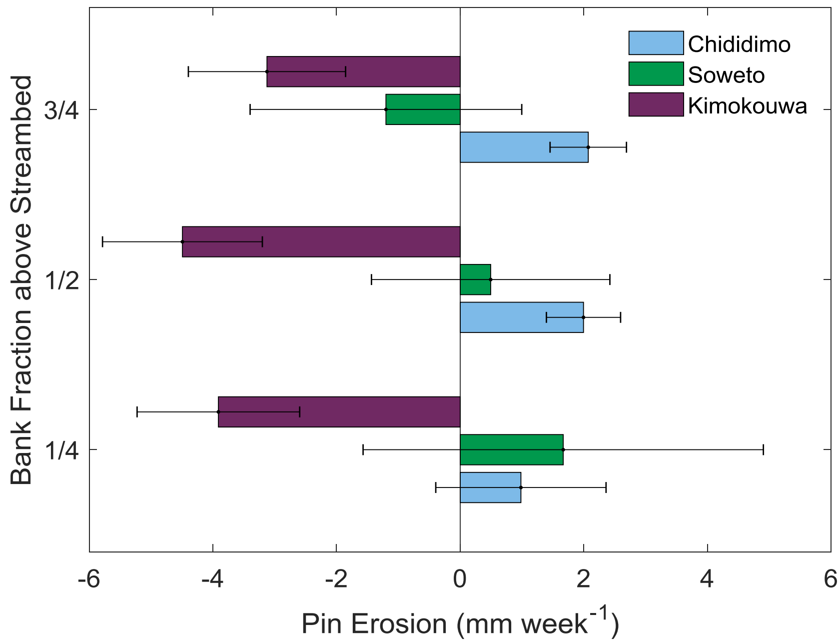

Figure 6: Average weekly change in the bank soil at ¼, ½, and ¾ bank height. Positive values represent deposition; negative values represent erosion. Standard error bars are shown.

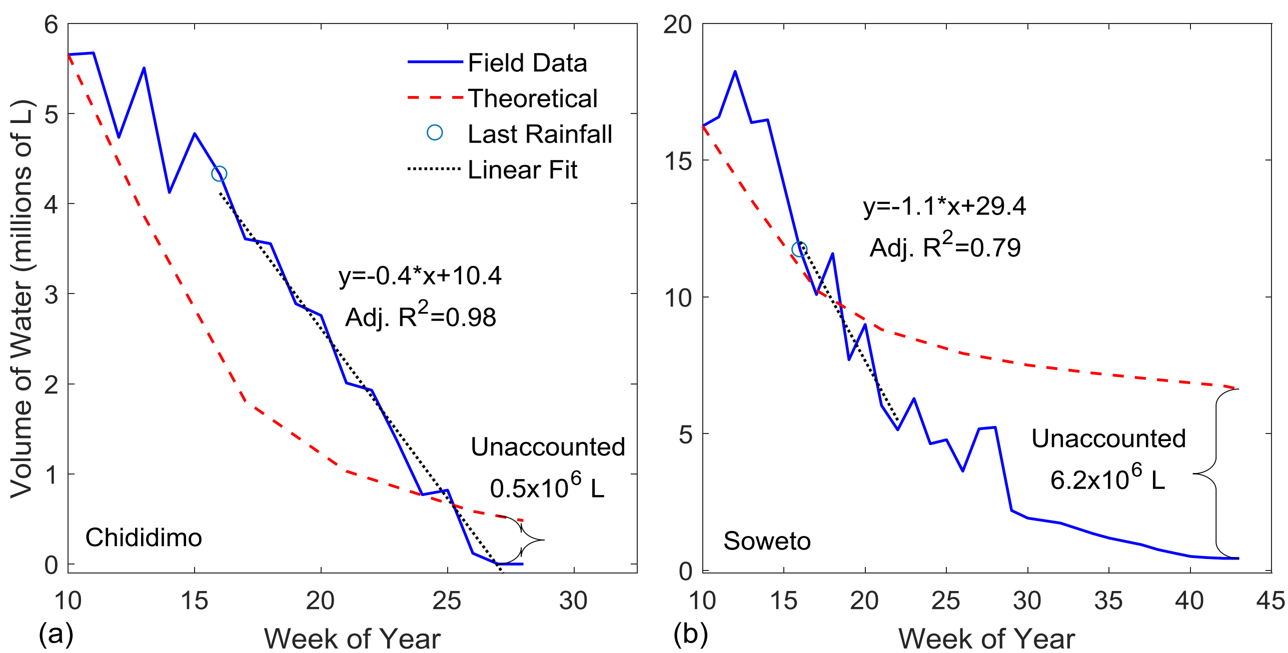

Figure 7: Volume of water in the (a) Chididimo and (b) Soweto sand dams. The field data line shows the volume of water in the sand dam during the specified week. The theoretical line shows the cumulative theoretical amount of water in the sand dam, calculated by integrating equation (1). The theoretical line accounts for rainfall, evapotranspiration, surface runoff, baseflow-groundwater runoff, and community use.

Table 1: Physical parameters of the three sand dams

Sand Dam	Total width (m)	Spillway (m)	Wing walls (m)	Spillway height (m)
Kimokouwa	28.78	8.74	20.04	2.06
Soweto	23.96	16.95	7.01	1.27
Chididimo	22.71	9.60	13.11	1.30

Table 2: Site characteristics of each erosion pin section

Sand Dam	Site Name	Bank	Length of bank pinned (m)	Bank height (m)	Bank morphology	Floodplain vegetation	Bank material	No. of pins	Pin spacing (m) V	Pin spacing (m) H	Date installed
	US1	left	5	3.7	gently sloping		silty sand	13	0.9	1	14/10/16
Kimokouwa	US2	right	6	5.2	composite	sparse trees and long grasses	silty sand and gravel	18	1.3	1	8/12/16
	DS	left	5	1.0	concave		clayey sand	15	0.2	1	24/11/16
	US1	left	4	2.4	vertical	large bushes and trees	silty sand	12	0.6	1	11/12/16
Soweto	US2	left	4	2.7	steeply sloping	long grasses, small bushes and trees	clayey sand and gravel	12	0.7	1	11/12/16
	DS	left	6	3.7	composite	long grasses and bushes	sand	18	0.9	1	11/12/16
Chididimo	US	right	9	3.7	composite	long grasses and bushes	sand	26	0.9	1	13/12/16

Note: US is upstream; DS is downstream; V is vertical (pin spacing); H is horizontal.

Table 3: Water table monitoring well installations at the three sand dams

Sand Dam	Number installed	Range of depths (m)	Average (m)	Standard deviation (m)
Kimokouwa	21	0.6–2.6	1.4	0.6
Soweto	22	0.5–3.7	1.5	0.8
Chididimo	20	0.5–1.9	1.0	0.4