Response to Reviewer 1

We would like to thank dr. ir. Rolf Hut for his constructive comments on the manuscript. We have considered his comments and provide the following responses.

Regarding the water balance model, I remain unconvinced that…the conclusion regarding ET can be drawn the way you do.

The uncertainty in the model remains, but we believe the updates to the model and calculations made at the request of Reviewer 3 will satisfy some of your misgivings regarding our conclusions. Changes in the calculations for the water balance model are described in the response to Reviewer 3.

We appreciate your continued scientific skepticism, as it has allowed us to refine our model and sharpen our discussion throughout this review process.

Response to Reviewer 2

We would like to thank Dr. Alison Parker for her constructive comments on the manuscript. We have considered her comments and provide the following responses.

I think it would be useful if they mentioned in the text that only three of the Tanzanian sand dams still have community water groups.

P3L12-13 has been updated to read: Only three of the community water groups formed during sand dam construction remained active at the time of this study.

They are relying on Hellwig (1973) to calculate evaporation from bare sand. (…) I would urge the authors to consider the new interpretations presented in: Quinn, R, Rushton, K., Parker, A, (2018) Evaporation from bare soil: lysimeter experiments in sand dams interpreted by numerical models, Journal of Hydrology 464, 909-915.

We did not calculate evaporation from bare sand using the methods suggested by Hellwig (1973). Estimates for ET were taken from the FLDAS dataset. Use of FLDAS has been clarified in the text (also at the request of Reviewer 3). Quinn et al. (2018b) has been added to the manuscript references, and the content was used to inform the discussion of ET losses, particularly for the three stages of ET loss rate. Thank you for bringing this manuscript to our attention.

P13L21-24 have been updated to read: The Soweto dam exhibits three distinct phases of water loss: shallow ET, deep ET, and minimal ET (see Fig. 9b; Quinn et al., 2018b). The minimal ET phase occurs during the period in which the community water group indicated they were no longer able to abstract water from the sand dam. At this point, the water table has retreated too far underground for the community to draw water and, at this depth, the rate of ET is likely negligible (Hellwig, 1973; Quinn et al., 2018b).

P14L1-2 have been updated to read: However, the dataset does not account for the depth at which the sand dam water is stored or for the unique features, such as wind speed, topography, vegetation, and shading, that impact ET rates (Hellwig, 1973; Quinn et al., 2018b).

Response to Reviewer 3

We would like to thank Dr. Tibor Stigter for his constructive comments on the manuscript. We have considered his comments and provide the following responses.

My main remark is that the collected groundwater level data allow a more comprehensive overview of the water table response at the three sand dam sites, including the non-functioning one. A total of 63 wells were drilled and water levels were monitored over one year (most successfully at Chididimo), which gives much more insight into the water table dynamics (in time and space) than described and discussed in the text. Moreover, the borehole logs from the 63 wells provide valuable lithological information for understanding connectivity between the (sand) river and its banks, which is now poorly addressed. The other component that I find a bit missing is the water quality aspect, which links directly to the apparently dominant mechanism of water loss in the areas, namely evapotranspiration (ET). If ET is indeed that dominant, as compared to lateral or vertical seepage, this should be seen in the increasing salinity of the water throughout the dry season, especially after a few years (the Soweto sand dam for instance was completed in 2011). It would be interesting to see if there is any additional information from EC measurements or interviews with the community that evidence a problem of increasing salinity.

A future work section has been added. After going through your comments, we realized that our 4th research question in the introduction and word choice throughout the manuscript were misleading. We frequently mentioned "water table" and "water table dynamics," but our analysis was focused on partitioning out the various loss mechanisms and discussing the factors impacting them. We have altered the language of our manuscript in many places to more accurately represent our analysis.

P16L1-7 have been added: Future analysis of the collected dataset will focus on exploring the spatial variability in the local geology and its interactions with groundwater in the vicinity of the sand dam. Water table dynamics will be investigated in conjunction with the variability of evapotranspiration in and around the sand dams. In addition, the change in vegetative cover relative to groundwater depth will be studied using both the field measurements detailed here and Normalized Difference Vegetation Index. Future sand dam research should also investigate water quality in the sand dams in the context of increasing salinity as evidence for or against high rates of evapotranspiration.

Abstract

Is well-written, but will need some editing after including additional results and discussion. It would be useful to read here why sand dams are not a suitable habitat for macroinvertebrates.

P1L9-10 have been updated: The study investigated a sand dam's impact on macroinvertebrate habitat, vegetation, and streambank erosion and explored a sand dam's water loss mechanisms.

P1L13-14 have been updated: The study found that sand dams are too homogeneous to provide the sustenance and refugia macroinvertebrates need at different life stages

Introduction

The response of the groundwater table in the surrounding area of a sand dam largely depends on the connectivity between that river margins and the sand river. This connectivity is often seen to be limited, which in part explains why the effect of an increasing water table is very local. This is not addressed in the text. The other aspect I would like to see introduced is that of sand dam water quality and processes (and/or human activities) that affect it.

A brief paragraph summarizing these relationships has been added to the introduction section.

P2L8-17 have been added: Sand dams are small, reinforced concrete dams built atop impermeable streambeds in arid regions with infrequent, high-intensity rainfall (see Fig. 1). The high-intensity rainfall *erodes soil from the land surface and deposits the coarser particles, usually sand, upstream of the dam. The sand stores primarily flash flood-water, where it is naturally filtered, protected from evaporation, and helps raise the groundwater level in the surrounding area due to recharge from the increased subsurface storage (Borst and de Haas, 2006; Hut et al., 2008; Quilis et al., 2009). The extent of a sand dam's impact on the groundwater level, however, is limited by the geologic connectivity between the sand dam and the riparian zone and by the community's water use rate (Hut et al., 2008; Quinn et al., 2019). While a sand dam does filter water in a process similar to a slow sand filter, water abstracted from sand dams via scoopholes and covered wells exceeds World Health Organization recommendations for turbidity (73 % exceedance), conductivity (24 % exceedance), and thermotolerant coliform concentration (55 % exceedance) (Quinn et al., 2018a).*

Study area

In the description of climate I would like to see average annual values of P, T and PET.

A few sentences with the requested information has been added to the study area.

P3L25-28 have been added: The average annual rainfall for Dodoma is 601 mm, and the potential evapotranspiration is 1800 mm. The average annual temperature in Dodoma is 23.0° C. The average annual rainfall for Longido is 696 mm, and the potential evapotranspiration is 1640 mm. The average annual temperature in Longido is 20.7° C (Platts et al., 2015).

The description of the geology is lacking. This is crucial information to discuss the connectivity between the (sand) river and its banks. As soil logs were collected from each of the 63 drillings, there is a lot of information available.

A brief description of the site geology for each sand dam was added to the study area.

P4L9-11 have been added: The soil deposited behind the Kimokouwa sand dam is largely silty sand with thick silt layers interspersed. In the riparian zone, the soil is primarily reddish sandy clay.

P4L17-18 have been added: The soil deposited behind the Soweto sand dam is moderately sorted sand, and the riparian zone is predominantly silty sand.

P4L25-26 have been added: The soil deposited behind the Chididimo sand dam is moderately sorted sand. The riparian zone contains primarily silty sandy gravel.

The characterization of the dimensions of the sand reservoirs built up behind the sand dams is missing. It would be important to state something about thickness, length and estimated storage capacity. In combination with the extinction depth this reveals the depth of "safe storage" not affected by ET. Only the maximum width (at the dam site) has been indicated for each area.

Unfortunately, MCC did not have any plan documents from when the sand dams were constructed, and we did not probe the bottom of the sand dams to generate cross sections. Therefore, we do not know the stream slope pre-dam. Based on the scoopholes dug by community members at Soweto and Chididimo and the depth achieved in the installed WTMWs, we estimate the depth of the sand dams to be around 2-3 m. At Kimokouwa, an exploratory borehole drilled just upstream of the sand dam reached a maximum depth of 2.6 m. These estimates for sand dam depth are consistent with those measured by Quinn et al. (2019) and are less than the 4-6 m estimate provided in Aerts et al. (2007).

Table 1 has been updated to show the requested information.

Table 1: Physical parameters of the three sand dams

Sand Dam	Total width (m)	Total length (m)	Spillway (m)	Estimated storage volume* (m^3)	Wing walls (m)	Spillway height (m)
Kimokouwa	28.78	150	8.74	1310	20.04	2.06
Soweto	23.96	350	16.95	5930	7.01	1.27
Chididimo	22.71	300	9.60	2880	13.11	1.30

**Note:* Storage volume estimated using an average sand dam depth of 2.5 m and porosity of 0.40. The spillway is approximately equal to the width of the stream channel.

P4L3-4 has been updated to read: All three sand dams vary in their construction specifications, length, and storage capacity (see Table 1).

An overall schematic diagram of a sand dam, and how it matures over time, would also be very useful. This would further help explain the non-functionality of the Kimokouwa sand dam.

The requested figure has been added as Figure 1.

The location of the hand pumps is not clear for the Kimokouwa and Soweto sand dams (where is "near the sand dam"?). For Chididimo why was the hand pump installed so far away from the dam?

Statements with this information have been added to the study area descriptions.

P4L10-11 have been updated to read: A hand pump was installed in the right bank, 30 m upstream of the sand dam in April 2016.

P4L18-19 have been updated to read: A hand pump was installed in the left bank, 85 m upstream of the sand dam at the time of dam construction.

P4L26-28 have been updated and expanded to read: A hand pump was installed within the stream channel 150 m upstream of the sand dam at the time of dam construction. The community selected this site for the hand pump, because they were able to extract water from the sandy streambed at that location before the sand dam was constructed.

Why was there no observation well placed directly behind (upstream of) the sand dam, in the middle of the river? This would have allowed to measure the fluctuations that are not affected by transpiration (only evaporation, seepage and abstraction).

Fair point, and perhaps a WTMW directly behind the sand dam would have yielded interesting results. However, we chose not to install any WTMWs directly in the sand dam. This has been done for other studies (see Borst and de Haas, 2006; Quinn et al., 2019), but we did not want to disrupt the functions of the sand dam or cause any potentially negative side effects with our research.

For the water table monitoring wells (WTMW) was topographic elevation of the top of the pipe measured, and with what accuracy?

A statement with this information has been added to section 3.5 Water table monitoring.

P6L31-32 have been added: The elevation of the top of the WTMW pipes was measured relative to the ground surface with a tape measure, accurate to the nearest cm. The ground elevation at the WTMWs was determined with a calibrated GARMIN GPSMAP 64s.

The water balance and resulting volumetric water loss calculations require some clarification. It is not clear how the "control volume" and corresponding water volume were calculated. I understand from the text that water volumes were integrated over the area covered by the monitoring wells. But how did the authors take the spatial variation in texture and related porosity into account?

This was not clearly explained in the manuscript. A paragraph describing the calculations has been added. The calculations were adjusted to account for variations in soil texture, altering our weekly water volumes figure (now Fig. 9) and resulting conclusions.

P7L17-25 have been added: The weekly average height of subsurface water in each WTMW was calculated from the field data, accounting for the difference in soil porosity between the sand dam and the riparian zone. A value of 0.42 was used for the porosity in the sand dam; 0.40 was used for the porosity in the riparian zone (Rawls et al., 1982). Inverse distance weighting interpolation was applied to create uniformly spaced grids of average water height at a weekly time step. The weekly average water volume was then calculated by multiplying the water height grids by the grid spacing and summing across the control area. The control area is the portion of the study area enclosed by the installed WTMWs (see Fig. 2 c,d). For Chididimo, this area is 32 274 m^2, while it is 41 995 m^2 for Soweto. The weekly average control area water volume calculated from the field data is compared to a theoretical weekly average water volume, described below.

How did the texture of the margins compare with that of the river bed?

We believe this question was suitably addressed in our response to your inquiries about site geology. The changes made are included again for ease of reference.

P4L9-11 have been added: The soil deposited behind the Kimokouwa sand dam is largely silty sand with thick silt layers interspersed. In the riparian zone, the soil is primarily reddish sandy clay.

P4L17-18 have been added: The soil deposited behind the Soweto sand dam is moderately sorted sand, and the riparian zone is predominantly silty sand.

P4L25-26 have been added: The soil deposited behind the Chididimo sand dam is moderately sorted sand. The riparian zone contains primarily silty sandy gravel.

What was the spatial distribution of the water table and the spatial variation in water table response to the sand river. Did the water table in the margins actually respond to the river level recharge or to aerial recharge from rainfall? This could be shown through piezometric maps at different moments of the year (end of the wet season and dry season) to check the losing or gaining behaviour of the sand dam. With so many well level recordings in time and space this invaluable information could be provided. It will also allow showing the importance of ET vs. direct soil evaporation (at places and/or times in the year where/when vegetation is absent). It will further allow to assess if lateral flow towards the river margin occurs, as hypothesized by the authors.

Thank you for your comment and ideas for additional analysis. We agree that this is valuable information and an interesting opportunity to expand the findings from the data we collected. We are conducting a more thorough analysis of the water table/sand dam dynamics for another manuscript, however, so these findings will not be included in this manuscript. We chose to limit the water table discussion here to keep the manuscript to a reasonable length, because we also covered macroinvertebrates, vegetation, and erosion at the sand dams. As written, the manuscript is intended to provide information on the data collected and discuss the overall trends in that data. We realize that the fourth research question listed in the Introduction section is misleading, so it has been updated to reflect the water storage and loss analysis presented in this manuscript.

P3L4-5 have been updated to read: (4) What are the dominant mechanisms driving water loss from a sand dam and the riparian zone?

FLDAS calculations should be better explained. In section 4 the authors mention that the FLDAS dataset calculates evaporation from bare soil based on simulated soil moisture content. How does this compare to transpiration, and how is the reduction of E and T with depth taken into account?

Additional information on the FLDAS dataset was added to the manuscript, with particular focus on how the dataset calculates transpiration and evaporation.

P7L28-31 have been added: FLDAS is a set of models designed to provide accurate climate estimates for the purpose of drought monitoring in data-sparse regions susceptible to food and water security issues (McNally et al., 2017). FLDAS provides daily and monthly climate data consisting of 25 different variables for Western, Eastern, and Southern Africa.

P8L18-22 have been added: FLDAS calculates transpiration by scaling potential evapotranspiration in proportion to solar radiation, vapor pressure deficit, air temperature, and soil moisture. Evaporation from bare soil in the FLDAS dataset is calculated by scaling potential evapotranspiration based on current soil moisture (McNally et al., 2017). Therefore, the rates of transpiration and evaporation in the FLDAS dataset will decrease as the water table retreats from the ground surface and soil moisture declines

Canopy-interception of rainfall should be entirely excluded from the water loss calculations, unless you include rainfall as an input to the water balance. If only ET from the subsurface is considered (water table, soil moisture) then including canopy interception makes no sense, even in the riparian corridors.

This is correct. The description of Eq. (1) has been updated to reflect this, and the calculations have been re-done to apply a modifier of 0.85 to the FLDAS ET data for the entire control volume.

P8L2-5 has been updated to read: where $Q_{out,dry\ season}$ *is the rate of water loss from the sand dam after the end of the rainy season,* E *is total evapotranspiration modified by* α*, which is 0.85,* Q_{sb} *is baseflow-groundwater runoff, and* Q_{com} *is the community's water use.*

P8L14-15 has been updated to read: Eq. (1) is only applied during the dry season, and therefore the control volume will not lose water due to evaporation of canopy-intercepted rainfall.

P8L18 has been updated to read: Therefore, total evapotranspiration is reduced by 15 % in Eq. (1), resulting in an α of 0.85.

Please explain how Qsb(t) (baseflow-groundwater runoff) was determined in the field. It is not mentioned.

Qsb(t) was not determined in the field. The value used for Qsb was taken from FLDAS data. A sentence has been added to clarify this.

P8L3-5 have been added: E *and* Q_{sb} *are taken directly from the FLDAS dataset (McNally et al., 2017), while* Q_{com} *was calculated based on each community's accounting of their water use.*

Sand dam impact

I recommend to name this section Results and Discussion, which you then separate per topic. Section 5 could then be General Discussion and Considerations, and then the Conclusions section is perhaps not really necessary.

The sections were re-named, as suggested. The conclusion section has been removed in favor of a Future Work section.

P8L28 now reads: 4 Results and Discussion

P14L22 now reads: 5 General Discussion and Considerations

P16L1 now reads: 6 Future Work

4.2 Vegetation: The authors provide evidence to support the statement that "it is reasonable to expect that the vegetative cover at the Soweto and Chididimo sand dams is improved, in part, by a locally raised water table near the ground surface". The arguments are clear, but could be further supported by the water level measurements, which are not shown.

We thank the reviewer for his ideas on how to strengthen our arguments. However, we are struggling to include this information on our existing figures without compromising their clarity. We will consider showing the relationship between depth to the water table and vegetated cover in future manuscripts.

I do wonder why at the lowest elevation vegetation is most sparse in the dry season.

We believe this is because the lowest elevation vegetation shown in Fig. 5a is below the ordinary high water mark for the streams. Vegetative growth below the ordinary high water mark is inhibited, but the abundance of water available at the sand dam margins during the wet season gives rise to rapid plant growth. This relationship is mentioned in P10L12-13: "As Fig. 5a indicates, there is low vegetative cover right at the stream edge (lowest elevation), which signifies streamflow frequently rising above this point and inhibiting vegetation growth."

Moreover, I do not agree that the fact that Kimokouwa has a very low vegetation cover in both the dry and wet season is related to a poorly functioning sand dam. It seems much more related to the topography, with higher elevations and slopes, and hence higher runoff and lower infiltration potential. For vegetation the role of groundwater can be important, but the role of the infiltration and water-holding capacity of the soil can be at least as relevant. In finer soils and flatter topography you will therefore expect more vegetation. The role of the sand river is questionable, with a few exceptions shown in Figure 3 (VT4 wet season Soweto, VT2 dry season Chididimo, and perhaps VT3-4 wet season Kimokouwa).

You are correct, land slope and soil play a big role in land cover. A statement acknowledging such was added.

P10L31-32 has been added: This may be due solely to the impact of the sand dams, but it is equally likely that the steeper slopes and finer soils at Kimokouwa impact its vegetative cover.

P10L34 has been added: Land slope and soil, however, must also be considered

4.3 Streambank erosion: clear and well supported by the observations; I am only not sure why the downstream curve for Chididimo is missing.

As mentioned in section 3.4 Erosion Study, erosion pins were only placed at one location at Chididimo. This sentence has been updated for clarity.

P6L9-11 were updated to read: Pins were installed at fewer locations 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.

4.4 Water Table: As mentioned, this section could be enriched by showing the results of the 12-hourly measurements taken at Chididimo and Soweto, to show the temporal and spatial variations of the

water table and how they related to the sand dam water level. The borehole log data could be shown to address the connectivity between river and banks, and the potential for groundwater flow into the banks. In many cases this connectivity is actually rather limited, even when sand dam water level is able to rise above the regional water level in the margins. That is probably another reason why the sand dam at Kimokouwa was non-functional, as the river valley is steeply incised (as in figure 5a), creating a small narrow sand reservoir with limited storage capacity and no possibilities to actually feed the neighbouring water table, which is expected to be above the sand dam level. Again, this could be verified with the water level data where they are available.

We appreciate your ideas for further analysis. We believe this content is more appropriate for a second paper, as mentioned previously. You are correct that limited connectivity between the Kimokouwa sand dam and its riparian zone could explain why the dam is non-functioning. This is supported by the fact that none of the Kimokouwa WTMWs had water, except for the one WTMW closet to the dam wall.

P12L3-6 have been added: Kimokouwa sand dam's water storage is also likely limited by the poor connectivity between the silty sand in the channel and the reddish clay that dominates the riparian zone. Groundwater is unable to travel freely between the sand dam and the riparian zone, as evidenced by the absence of water in all but one WTMW.

How is the 1% of the total water lost attributed to baseflow determined?

The volume of total water lost is based on the field data calculations. The portion of the water lost attributed to baseflow is the $Q_{sb}(t)$ term in Eq. (1), which comes directly from the FLDAS dataset. We have added a sentence to section 3.5 to clarify that the $Q_{sb}(t)$ term comes from FLDAS.

P8L3-6 have been added: E and Q_{sb} *are taken directly from the FLDAS dataset (McNally et al., 2017), while* Q_{com} *was calculated based on each community's accounting of their water use.*

In Figure 8 show how the red line was calculated and add the ET line for comparison.

The caption of (now) Figure 9 includes a description of how to calculate the theoretical line. We added a bit more detail to the explanation and believe this is adequate to inform the reader of the basis for the theoretical line.

Figure 9 caption now reads: The theoretical line, initiated at the end of the rainy season, shows the theoretical volume of water in the study area, calculated by integrating Eq. (1) and subtracting from the field-determined volume of water at the end of the rainy season.

The theoretical ET line was added to (now) Figure 9. A description of the line was added to the caption.

Figure 9 caption now includes: The theoretical ET line shows the portion of total theoretical loss attributed to ET in the FLDAS dataset.

How does ET vary spatially in the areas? This is shown by the water table fluctuations? How do the variations below vegetative cover (dominated by ET) compare to those below bare soil (in particular the sand reservoir area, dominated by E)?

There is likely not much variety in ET across the Chididimo study area, because Chididimo is uniformly vegetated with natural vegetation and in a uniform stream valley. Conversely, the Soweto study area has large plots under cultivation, some sparsely vegetated areas, and some areas with dense natural vegetation and is topographically varied.

We are not convinced that our collected water table data can be used to accurately calculate ET in the study area, hence the adoption of FLDAS ET data for this analysis. Community volunteers recorded WTMW measurements to the nearest cm. Therefore, the data lacks the precision of typical ET data. In addition, because the sand dam represents an open system with multiple sources of loss, we cannot necessarily attribute all water depth changes measured at the wells to ET. Community use, baseflow, and seepage through cracks in the bedrock or under the sand dam all contribute to the declining water table. To determine how ET varies spatially across the study areas, we should have installed a series of lysimeters.

We will investigate whether conclusions can be drawn about the spatial variability of ET when we conduct a more thorough analysis of water table dynamics around the sand dam for our planned second manuscript. However, as mentioned above, the uncertainty of these calculations is likely to be an issue.

The fact that Chididimo and Soweto experience approximately 100 mm lower rainfall than in Kenya is not the cause of faster storage depletion throughout the dry season. It is the length of the rain season and the duration/frequency of river flow that determines whether a sand dam lasts longer. This is actually addressed in the discussion.

That is true. The text in section 4.4 has been updated to clarify why the lower annual rainfall in Dodoma limits the sand dams' potential as a water resource.

P14L175-20 have been updated: At Chididimo and Soweto, this is simply not the case. Chididimo and Soweto experience approximately 100 mm lower annual rainfall in one, four-month rainy season and higher rates of ET than a typical sand dam in Kenya experiences during two rainy seasons (NASA/GSFC/HSL, 2016). Therefore, the Dodoma sand dams have lower potential for storing water than their Kenyan counterparts.

The authors state correctly that "The Soweto sand dam is losing water during the shallow ET phase at nearly 2.5 times the rate of the Chididimo sand dam." They argue that this is because: "The width of the Soweto sand dam is nearly twice that of Chididimo, providing a greater surface area of sand from which evaporation occurs". However, the rate is already given in mm/day, independent of area. It is more likely, also by looking at the elevations in Figures 1c/1d, that the water levels are overall much shallower in the Soweto area. This would also show in the water table monitoring data. In that case, the grey area in Figure 8a would actually correspond to "Deep ET" or "Intermediate ET" in Chididimo, rather than shallow ET. The difficulty here is that for the calculations not only the sand dam itself is considered, but also the surrounding area. It would be interesting to compare this to the calculations only for the sand reservoir behind the sand dam.

We thank the reviewer for his comment and acknowledge that, as written, the text could be confusing. We rearranged the paragraph, as detailed below, and removed the reference to seepage. As an additional note, the water levels at Soweto are, on average, approximately 0.5 m deeper than at Chididimo. Chididimo, indeed, has shallower groundwater levels near the sand dam compared to Soweto.

P14L7-14 were rearranged: The Soweto sand dam is losing water during the shallow ET phase at more than twice the rate of the Chididimo sand dam. The combination of stream width and vegetative cover contribute to Soweto's higher rate of water loss. The width of the Soweto sand dam is nearly twice that of Chididimo, providing a greater surface area of sand from which evaporation occurs (see Table 1). For an equivalent water content, sub-surface evaporation rates from sand in the sand dam are higher than from the loamy soils in the riparian zone due to the differences in soil suction (Wilson et al., 1997). 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.*

5. Discussion

The authors mention that "the functioning sand dams had significant impact on the local water table", but do not provide the evidence to support this. This would require knowledge on the water table dynamics before the sand dams were constructed, or the thickness of the sand deposits/total capacity of the sand reservoir before the sand dam was built. It is obvious that there will have been impact, but at least try to show it through the observed water level behaviour after the dam was built, showing the extent to which the sand dam had an effect.

You are correct, the evidence provided in this manuscript does not support this statement. Because we are not intending to cover the water table dynamics in this manuscript, we have adjusted this statement to reflect the presented results.

P14L25-26 have been updated to read: The field study revealed that a non-functioning sand dam might significantly influence streambank erosion but has little impact on the local water storage …

P14L26-28 have been updated to read: The functioning sand dams, however, had little impact on streambank erosion, significant impact on local water storage and in reducing ET losses, and varied impact on vegetation.

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, and streambank erosion~~,~~ and ~~the local~~explored a sand dam's water ~~table~~loss mechanisms. 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~~found that sand dams are ~~not a suitable habitat for~~too homogeneous to provide the sustenance and refugia macroinvertebrates need at different life stages. 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 tell 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.

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 3000 sand dams, yet approximately 50 % of sand dams are essentially non-functioning (de Trincheria et al., 2018; Viducich, 2015).

Sand dams are small, reinforced concrete dams built atop impermeable streambeds in arid regions with infrequent, high-intensity rainfall (see Fig. 1). The high-intensity rainfall erodes soil from the land surface and deposits the coarser particles, usually sand, upstream of the dam. The sand stores primarily flash flood-water, where it is naturally filtered, protected from evaporation, and helps raise the groundwater level in the surrounding area due to recharge from the increased subsurface storage (Borst and de Haas, 2006; Hut et al., 2008; Quilis et al., 2009). The extent of a sand dam's impact on the groundwater level, however, is limited by the geologic connectivity between the sand dam and the riparian zone and by the community's water use rate (Hut et al., 2008; Quinn et al., 2019). While a sand dam does filter water in a process similar to a slow sand filter, water abstracted from sand dams via scoopholes and covered wells exceeds World Health Organization recommendations for turbidity (73 % exceedance), conductivity (24 % exceedance), and thermotolerant coliform concentration (55 % exceedance) (Quinn et al., 2018a).

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). A comprehensive study of three Kenyan sand dams explored their hydrology and bare soil evaporation, while a survey of at least 50 sand dams analysed their water quality (Quinn et al., 2018a; Quinn et al., 2018b; Quinn et al., 2019). 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~~and the ~~ideal~~Quinn et al. (2018b, 2019) studies on high-functioning sand ~~dam~~dams, 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 examines claims made by non-scientific bodies about sand dam impacts by investigating how diverse sand dams influence macroinvertebrate habitat, vegetation, erosion, and ~~groundwater recharge in the riparian zone.~~local water availability. Specifically, the study will investigate 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~~ What are the dominant mechanisms driving water loss from the sand dams ~~alter the groundwater table in the surrounding area~~and riparian zone? Answering these questions will provide some insight into the validity of the claim that sand dams revitalize the entire ecosystem (Reversing Land Degradation and Desertification, n.d.; Sand Dams, n.d.). These questions will be explored 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 provides a broad representation of the sand dams found throughout the region, and this study will therefore create a better understanding of how a sand dam interacts with the local environment. The study is limited to only three sand dams, because the study design relies on the active participation of local community water groups. ~~Most~~Only three of the community water groups formed during sand dam construction ~~had disbanded~~remained active at the time of this study. The breadth of the study was further limited by long travel times between sites and difficulties related to equipment access.

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 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~~2a; 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~~2a). Most of the sand dams were funded by the Mennonite Central Committee of Tanzania (MCC) and designed by Kenya-based NGOs. Dodoma has nine sand dams; Longido, a small town near the Kimokouwa sand dam (see Fig. ~~1a~~2a), has four sand dams, and there are a few sand dams elsewhere in the country. The average annual rainfall for Dodoma is 601 mm, and the potential evapotranspiration is 1800 mm. The average annual temperature in Dodoma is 23.0° C. The average annual rainfall for Longido is 696 mm, and the potential evapotranspiration is 1640 mm. The average annual temperature in Longido is 20.7° C (Platts et al., 2015).

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, length, and storage capacity (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~~2b) 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. The soil deposited behind the Kimokouwa sand dam is largely silty sand with thick silt layers interspersed. In the riparian zone, the soil is primarily reddish sandy clay. A hand pump was installed ~~near~~in the right bank, 30 m upstream of 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~~2c) 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 soil deposited behind the Soweto sand dam is moderately sorted sand, and the riparian zone is predominantly silty sand. A hand pump was installed in the left bank, 85 m upstream of 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.~~for irrigation. 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~~2d) 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. The soil deposited behind the Chididimo sand dam is moderately sorted sand. The riparian zone contains primarily silty sandy gravel. A hand pump was installed ~~180~~within the stream channel 150 m upstream of the sand dam at the time of dam construction. The community selected this site for the hand pump, because they were able to extract water from the sandy streambed at that location before the sand dam was constructed. 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 rainy 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~~2 b,c). At Kimokouwa, where the stream is narrow, the centre of each transect lay at the middle of the stream (see Fig. ~~1d~~2d).

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~~Pins were installed at fewer locations 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~~, 300 mm deposition ~~event,~~was assumed, and 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~~2b-d for WTMW layout at the sand dams. Fig. ~~2~~3 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).~~3). The elevation of the top of the WTMW pipes was measured relative to the ground surface with a tape measure, accurate to the nearest cm. The ground elevation at the WTMWs was determined with a calibrated GARMIN GPSMAP 64s.

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~~per 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~~most complete understanding of how ~~the~~ water ~~table fluctuates near a~~ storage in the sand dam changed over time.

The water table measurements were used to determine the volume of water in the sand dam and riparian zone over time. The weekly average height of subsurface water in each WTMW was calculated from the field data, accounting for the difference in soil porosity between the sand dam and the riparian zone. A value of 0.42 was used for the porosity in the sand dam; 0.40 was used for the porosity in the riparian zone (Rawls et al., 1982). Inverse distance weighting interpolation was applied to create uniformly spaced grids of average water height at a weekly time step. The weekly average water volume was then calculated by multiplying the water height grids by the grid spacing and summing across the control area. The control area is the portion of the study area enclosed by the installed WTMWs (see Fig. 2 c,d). For Chididimo, this area is 32 274 m^2, while it is 41 995 m^2 for Soweto. The weekly average control area water volume calculated from the field data is compared to a theoretical weekly average water volume, described below.

To ~~help~~ determine the various causes of water loss from the sand dam and their relative magnitude, a theoretical water balance was calculated using data from Famine Early Warning Systems Network Land Data Assimilation System (FLDAS). FLDAS is a set of models designed to provide accurate climate estimates for the purpose of drought monitoring in data-sparse regions susceptible to food and water security issues (McNally et al., 2017). FLDAS provides daily and monthly climate data consisting of 25 different variables for Western, Eastern, and Southern Africa. In this study, FLDAS data was used as a proxy for climate data, because there is not a reliable source of climate data freely available for Dodoma, Tanzania. The theoretical water loss from the sand dam is:

$$Q_{out,dry\ season}(t) = -\alpha \times E(t) - Q_{sb}(t) - Q_{com}(t)\ , \quad (1)$$

where $Q_{out,dry\ season}$ is the rate of water loss from the sand dam after the end of the rainy season, E~~(t)~~ is total evapotranspiration modified by α, which is 0.85~~ for the area within the sand dam and 1.00 for the riparian zone~~, Q_{sb} is baseflow-groundwater runoff, and Q_{com} is the community's water use. ~~Eq. ~~E and Q_{sb} are taken directly from the FLDAS dataset (McNally et al., 2017), while Q_{com} was calculated based on each community's accounting of their water use. Eq. (1) is integrated over time, t, and subtracted from the field data-determined volume of water in the control ~~volume~~area at the end of the rainy season to create a theoretical volume of water curve for the sand dam area~~.~~ (see Fig. 9). The control ~~volume~~area to which Eq. (1) is applied is that used for the field data water volume calculations: the portion of the study area ~~that is ~~enclosed by the installed WTMWs (see Fig. ~~1~~2 c,d).~~ For Chididimo, this area is 32 274 m^2, while it is 41 995 m^2 for Soweto.~~ The theoretical volume of water resulting from Eq. (1) has a high degree of uncertainty, because it is a simplified representation of water loss that utilizes modelled FLDAS data. However, the relative magnitude of the loss terms is likely reliable, and this is the primary focus of the conclusions that will be drawn from the model.

Total evapotranspiration, E~~(t),~~, is the sum of canopy-intercepted evaporation, transpiration from vegetation canopies, and evaporation from bare soil (McNally et al., 2017). ~~A sand dam~~Eq. (1) is only applied during the dry season, and therefore the control volume will not lose water due to evaporation of canopy-intercepted rainfall~~, so including~~. Including this portion of E~~(t)~~ 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~~) for~~), resulting in an α of 0.85. FLDAS calculates transpiration by scaling potential evapotranspiration in proportion to solar radiation, vapor pressure deficit, air temperature, and soil moisture. Evaporation from bare soil in the ~~portion of the control volume that~~FLDAS dataset is ~~occupied by ~~calculated by scaling potential evapotranspiration based on current soil moisture (McNally et al., 2017). Therefore, the rates of transpiration and evaporation in the ~~sand dam. ~~FLDAS dataset will decrease as the water table retreats from the ground surface and soil moisture declines.

The community's water use was calculated using estimates provided by the community water groups~~. The estimate of the community's use of water from the sand dam~~, and thus has an unknown degree of uncertainty. At least one sand dam researcher has noted that unsanctioned machine pumping of water from sand dams can cause rapid drawdown of stored water (Hut et al., 2008). However, no evidence was present at either Dodoma site to indicate the community was drawing significantly more water from the sand dams than they indicated.

~~4 Sand dam impact~~

4 Results and Discussion

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. The absence of macroinvertebrates in the sand dams might suggest that sand dams have a negative impact on macroinvertebrate habitat, but it is also likely that sandy streambeds in semi-arid regions are simply inhospitable to macroinvertebrates. To make this distinction, further studies are needed to compare macroinvertebrate assemblages in undammed sandy ~~riverbeds~~streambeds with those in sand dams. Of all substrates studied, Duan et al. (2008) identified sandy substrate to have the lowest taxa richness and to be the least suitable for macroinvertebrates and benthic fauna, causing sandy substrates to be fairly homogeneous. 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) and few 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 determined by a visual and tactile assessment of the material. 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~~4). Kimokouwa~~, unsurprisingly,~~ had the lowest level of vegetative cover overall and did not exhibit 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 (see Fig. ~~1d~~2d), 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.

That Soweto, the flattest site, and the two transects located in the flattest part of Chididimo display significant increases in vegetation between the dry and rainy seasons suggest that the average percent vegetative cover at a sand dam is correlated to the land slope near the sand dam. The Pearson Correlation Coefficient, ρ, corroborates this observation. The change in vegetative cover between the dry and rainy seasons is negatively correlated ($\rho = -0.73$) to increasing land slope at the two functioning sand dams, Soweto and Chididimo, indicating that as the land slope increases, the improvement in vegetative cover decreases. The same correlation is not observed at the non-functioning Kimokouwa sand dam ($\rho = 0.04$), which is expected because the sand dam is not contributing to a locally raised water table.

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~~5a). The trend of decreasing vegetative cover with increasing elevation above the streambed is more consistent during the dry season but is also evident during the rainy season. Two conditions may combine to create the trend seen in Fig. ~~4a~~5a. First, at low elevations above the streambed, groundwater seepage through the streambanks creates a raised water table that is close to the land surface (see Fig. ~~5~~6). The raised water table has a positive impact on the soil moisture of the unsaturated soil layer, and this additional moisture supports vegetation growth. Second, a lower elevation above the streambed implies a gentler land slope. Gentle slopes give rainwater more time to infiltrate into the soil, because storm surface runoff travels slower over a gentle slope. Increased infiltration results in increased soil moisture and increased recharge of the water table. As Fig. ~~4a~~5a indicates, there is low vegetative cover right at the stream edge (lowest elevation), which signifies streamflow frequently rising above this point and inhibiting vegetation growth.

That the dry season shows a consistent relationship between elevation above the streambed and vegetative cover indicates that the vegetation at Soweto and Chididimo has at least some level of groundwater dependence (see Fig. ~~4a~~5a). The dependence of vegetation on groundwater in arid and semi-arid regions has been well-documented (Elmore et al., 2008; Mata-González et al., 2012; Naumburg et al., 2005; Seeyan et al., 2014; Stromberg et al., 1996; Wang et al., 2011). In arid and semi-arid regions where rainfall is minimal, vegetation often relies on groundwater to supply the additional water needed for plant growth and transpiration (Naumburg et al., 2005). In semi-arid Dodoma, local communities use their knowledge of the relationship between vegetation and groundwater to inform their decisions on where to dig shallow wells (Shemsanga et al., 2018). Therefore, it is reasonable to expect that the vegetative cover at the Soweto and Chididimo sand dams is improved, in part, by a locally raised water table near the ground surface.

The upstream and downstream vegetative cover 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~~5b). 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. ~~However~~Nevertheless, additional studies are needed to verify this relationship. 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~~This may be due solely to the impact of the sand dams, but it is equally likely that the steeper slopes and finer soils at Kimokouwa impact its vegetative cover. A functioning sand dam has the potential to support more vegetation, because of the additional stored water that is available to vegetation for use in transpiration. Land slope and soil, however, must also be considered.

4.3 Streambank erosion

The temporal changes in the bank soil varied somewhat across the three sand dams (see Fig. ~~6~~7). Kimokouwa and Soweto exhibited little change in bank volume at the upstream locations, 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 location, 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~~nearly 300 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. ~~6~~7).

The spatial changes in bank soil also vary between the three sand dam sites (see Fig. ~~7~~8). 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 erroneously recorded 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. This erosion 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. The migration of the stream channel likely contributes to the mass erosion of the bank downstream of the sand dam (see Fig. ~~6~~7).

4.4 Water ~~Table~~storage and loss

The sand dam at Kimokouwa has a 1.2 m thick silt layer beginning at a depth of 0.5 m that acts as a capillary barrier, inhibiting the infiltration and, therefore, storage of water in the sand dam. ~~As a result~~Kimokouwa sand dam's water storage is also likely limited by the poor connectivity between the silty sand in the channel and the reddish clay that dominates the riparian zone. Groundwater is unable to travel freely between the sand dam and the riparian zone, as evidenced by the absence of water in all but one WTMW. As a result of limited storage, 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 topsoil present in the area (Nissen-Petersen, 2006; de Trincheria et al., 2015). While the literature on this topic is not well-developed, the soil composition of the streambed before a sand dam is constructed can likely be helpful in determining the distribution of grain sizes a sand dam is expected to capture. This information, coupled with knowledge of the sediment load typically carried by the stream, can inform the need to construct a sand dam's spillway in stages to prevent siltation. 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~~.~~ (see Fig. 1). 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 around early to mid-April, approximately the fourteenth or fifteenth week of the year. Fig. ~~8a~~9a 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. ~~8b~~9b). 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 ~~4~~10 % of the water stored by the sand dam at the end of the rainy season. Unsurprisingly, most of the water in the sand dam is lost to evapotranspiration (ET). With only ~~1~~2 % of the total water lost during the dry season attributed to baseflow-groundwater runoff~~ and 42% unaccounted~~, ET was responsible for ~~at least 53~~the remaining 88 % of the water lost from the Chididimo sand dam according to FLDAS data and Eq. (1) (see Fig. ~~8a). The unaccounted~~9a). Eq. (1) predicted the sand dam would lose its stored water by week 23. The measured data indicates the sand dam retained water until week 27. Furthermore, Fig. 9a shows that the sand dam experienced a loss ~~could be due to seepage through the streambanks or streambed or possibly a higher rate~~reduction of 400 000 litres during the first twelve weeks of the dry season. This suggests the dam effectively reduced ET ~~than~~by 19 % compared to the ET simulated by FLDAS.

The nearly constant decrease in water volume, or total loss rate (L_T), after the end of the rainy season at the Chididimo sand dam indicates that ~~the~~most water is ~~likely~~ lost due to ET (see Fig. ~~8a~~9a). Chididimo's relatively shallow sand reservoir results in all ET occurring at a shallow ET rate. When ET occurs from a sub-surface water table, the rate of ET is lower than would be expected if the water table was at the ground surface (Hellwig, 1973). The rate of sub-surface ET decreases as the water table retreats farther underground, and the rate of decrease is dependent upon depth and grain size (Hellwig, 1973~~).~~; Quinn et al., 2018b). Seepage could ~~be contributing~~contribute to the total loss rate at Chididimo. While there was no evidence of seepage under the dam wall, downward seepage through the streambed could impact the total loss rate at Chididimo.

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 ~~4~~10 % of the water stored by the sand dam at the end of the rainy season. With only 1 % of the total water lost attributed to baseflow-groundwater runoff and ~~60 %~~16 % of loss unaccounted by FLDAS, ET was responsible for ~~at least 35~~65 % of the water lost from the Soweto sand dam according to Eq. (1) (see Fig. ~~8b~~9b). The unaccounted water loss could be due to seepage under the sand dam wall, through the streambanks, or streambed ~~or possibly~~combined with a ~~higher~~lower rate of ET than simulated by FLDAS.

The Soweto dam exhibits three distinct phases of water loss: shallow ET, deep ET, and minimal ET (see Fig. ~~8b).~~9b; Quinn et al., 2018b). The minimal ET phase occurs during the period in which the community water group indicated they were no longer able to abstract water from the sand dam. At this point, the water table has retreated too far underground for the community to draw water and, at this depth, the rate of ET is likely negligible (Hellwig, 1973~~).~~; Quinn et al., 2018b). Therefore, most of the water lost during the minimal ET phase is lost due to seepage under the dam wall and/or through the streambed. Unlike Chididimo, the Soweto sand dam does exhibit evidence of seepage—the community members collect water from scoopholes they dig just downstream of the dam. The seepage loss at Soweto occurs at a rate of approximately 0.~~4~~2 mm day^{-1} and accounts for ~~25~~24 % of the water stored by the sand dam at the end of the rainy season~~, leaving only 35 % of Soweto's water loss unaccounted~~. The seepage rate is assumed to remain essentially constant throughout the shallow, deep, and minimal ET phases (see Fig. ~~8b~~9b). Having accounted for seepage, Fig. 9b shows that the ~~remaining 35 % unaccounted water~~sand dam experienced a loss ~~at Soweto is likely lost primarily due~~reduction of 600 000 litres during the first 29 weeks of the dry season. This suggests the dam effectively reduced ET by 11 % compared to ~~ET.~~the ET simulated by FLDAS.

Fig. ~~8~~9 shows that the sand dams lost water at a ~~faster~~slower rate than predicted by Eq. (1) during the dry season. ~~ET is occurring 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 the ~~additional water available in the perched aquifer created by the sand dam's stored water.~~depth at which the sand dam water is stored or for unique features, such as wind speed, topography, vegetation, and shading, that impact ET rates (Hellwig, 1973; Quinn et al., 2018b). The lines fit to the field data after the end of the rainy season indicate that the Chididimo and Soweto sand dams are losing water primarily via ET at a nearly constant rate of ~~1~~0.7 mm day^{-1} and ~~4.4~~1.6 mm day^{-1}, respectively. ~~This high rate of~~Due to ET ~~means that~~and other major losses, 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 shallow ET phase at ~~nearly 2.5 times~~more than twice the rate of the Chididimo sand dam. The combination of stream width and vegetative cover contribute to Soweto's higher rate of water loss. The width of the Soweto sand dam is nearly twice that of Chididimo, providing a greater surface area of sand from which evaporation occurs (see Table 1). For an equivalent water content, sub-surface evaporation rates from sand in the sand dam are higher than from the loamy soils in the riparian zone due to the differences in soil suction (Wilson et al., 1997). 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 an issue at the Soweto sand dam, as previously mentioned. 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 in one, four-month rainy season and higher rates of ET than a typical sand dam in Kenya experiences during two rainy seasons (NASA/GSFC/HSL, 2016). Therefore, the Dodoma sand dams have lower potential for storing water than their Kenyan counterparts. Sand dams are intended to protect the stored water from evaporation and they do to some extent, but the ground surface is inadequate protection against the high temperatures and dry air at the Chididimo and Soweto sand dams.

5 General Discussion ~~of impacts~~ and ~~recommendations~~Considerations

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~~storage and vegetation. The functioning sand dams, however, had little impact on streambank erosion, significant impact on ~~the~~ local water ~~table~~storage and in reducing ET losses, 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 limit the value of ecosystem services, such as nutrient cycling, decomposition of organic matter, or primary productivity. The lack 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 (see Fig. ~~5~~6). The increased soil water near the land surface is available to support vegetative growth and transpiration, leading to higher vegetative cover. Holding all other variables constant, building a sand dam in a flat area would likely maximize the positive impact of the sand dam on local vegetation. However, this needs to be further explored to see if the trend holds when more sand dams are examined.

The two functioning sand dams have stable streambanks compared to the non-functioning Kimokouwa sand dam. The streambanks at Kimokouwa exhibit severe erosion, particularly at the site downstream of the sand dam. The Kimokouwa sand dam was constructed between two 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 likely contributes to the migrating of the Kimokouwa stream channel. Severe streambank erosion and/or stream migration can lead directly to sand dam failure by weakening the soil supporting the structure. When this happens, the dam may break or be washed downstream. Sand dams should probably 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 refilling the sand dams 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 ET than the annual rainfall and average ET at the Kenyan sand dams. Less rainfall limited to one rainy season of the year and higher ET 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 ET. While the Chididimo and Soweto sand dams ~~help~~helped slow the rate of ET by 19 % and 11 %, respectively, ET is still the greatest loss factor for the stored water. Chididimo has a shallower sand dam and lost ~~at least 53~~88 % of its stored water to ET, while Soweto is deeper and lost ~~at least 35~~65 % of its stored water to ET. ~~However, the 42 % and 35 % unaccounted loss at Chididimo and Soweto, respectively, was likely lost primarily via ET. Typically up to 65 % of rainfall is lost to ET (Trenberth et al., 2007), but the ET losses at the two sand dams exceeded this rate.~~ The deeper Soweto sand dam lost less water to ET 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~~).~~; Quinn et al., 2018bf). To help reduce the amount of water lost from sand dams due to ET, sand dams should likely be constructed in locations where a deep sand reservoir can develop. At least one other study, de Trincheria et al. (2015), also recognised the impact of shallow sand reservoirs on water lost to ET.

6 ~~Conclusions~~Future Work

~~An in-depth field study of three diverse sand dams was performed to improve 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 the homogeneity of sand dams. Overall, the functioning sand dams support increased vegetative growth, but the improvement appears to be 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 bank change was largely observed at the two functioning sand dams. Finally, the functioning sand dams have a positive, but evaporation and seepage 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 and when assessing the effectiveness of existing structures. Per the study findings, sand dams should likely be constructed in a flat area and constructing them in a stable stream seems essential. Despite a design intended to reduce ET losses, sand dams still experience a high rate of ET. Clever solutions for mitigating ET 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.~~

Future analysis of the collected dataset will focus on exploring the spatial variability in the local geology and its interactions with groundwater in the vicinity of the sand dam. Groundwater dynamics will be investigated in conjunction with the variability of evapotranspiration in and around the sand dams. In addition, the change in vegetative cover relative to groundwater depth will be studied using both the field measurements detailed here and Normalized Difference Vegetation Index. Future sand dam research should also investigate water quality in the sand dams in the context of increasing salinity as evidence for or against high rates of evapotranspiration.

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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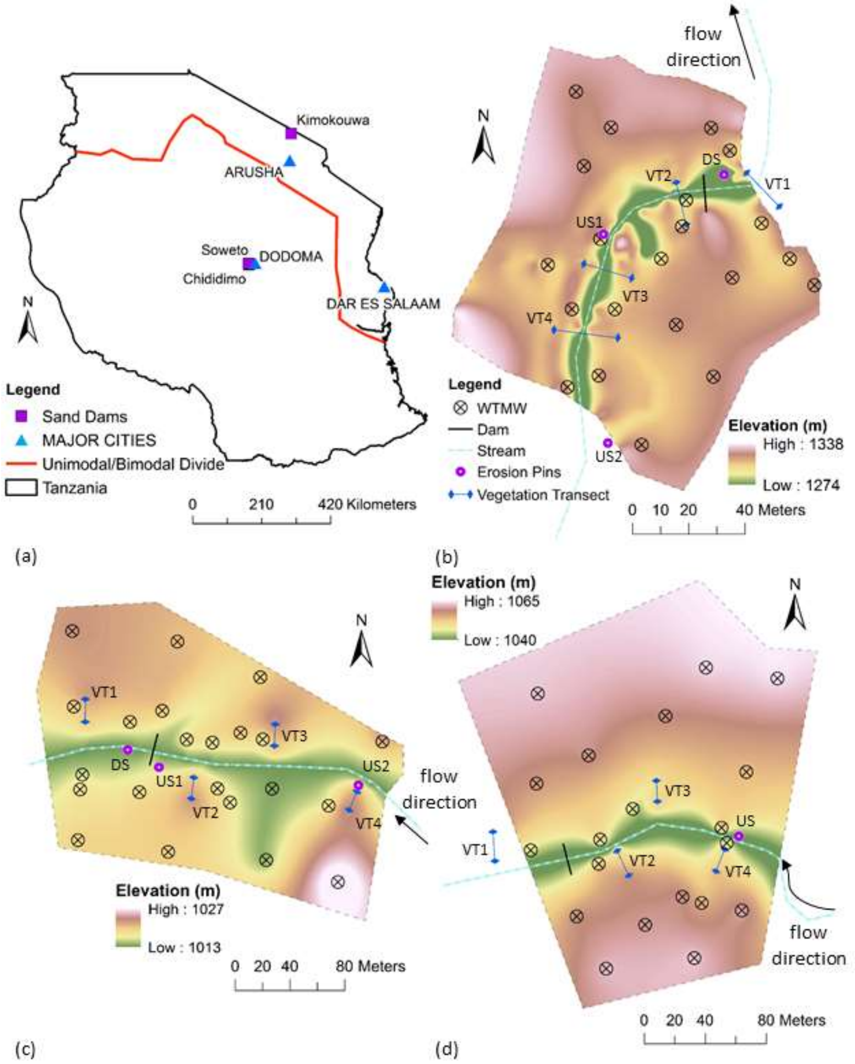


Kimokouwa
ARUSHA
Soweto
DODOMA
Chididimo
DAR ES SALAAM
N
Legend
Sand Dams
MAJOR CITIES
Unimodal/Bimodal Divide
Tanzania
0 210 420 Kilometers
(a)
flow direction
N
DS
VT1
VT2
US1
VT3
VT4
US2
Legend
WTMW
Dam
Stream
Erosion Pins
Vegetation Transect
Elevation (m)
High : 1338
Low : 1274
0 10 20 40 Meters
(b)
N
VT1
VT3
DS
US1
VT2
US2
VT4
flow direction
Elevation (m)
High : 1027
Low : 1013
0 20 40 80 Meters
(c)
Elevation (m)
High : 1065
Low : 1040
N
VT3
VT1
VT2
US
VT4
flow direction
0 20 40 80 Meters
(d)

~~Figure 1~~

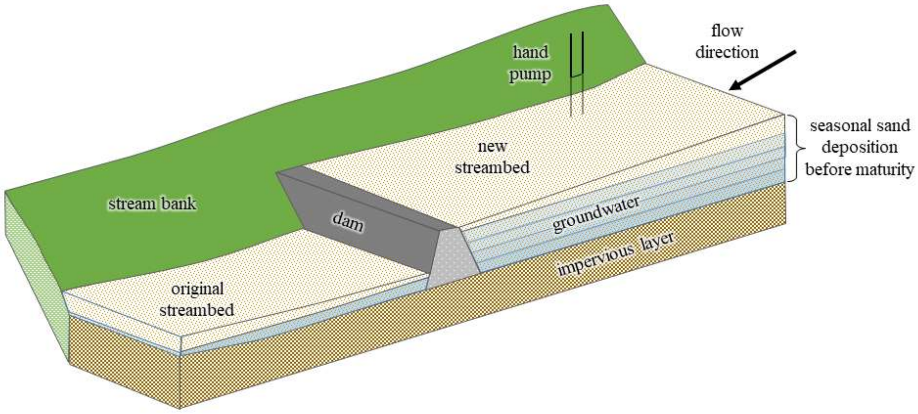


Figure 1: Schematic of a sand dam showing seasonal sand deposition before the dam reaches maturity (adapted from Borst and de Haas, 2006).

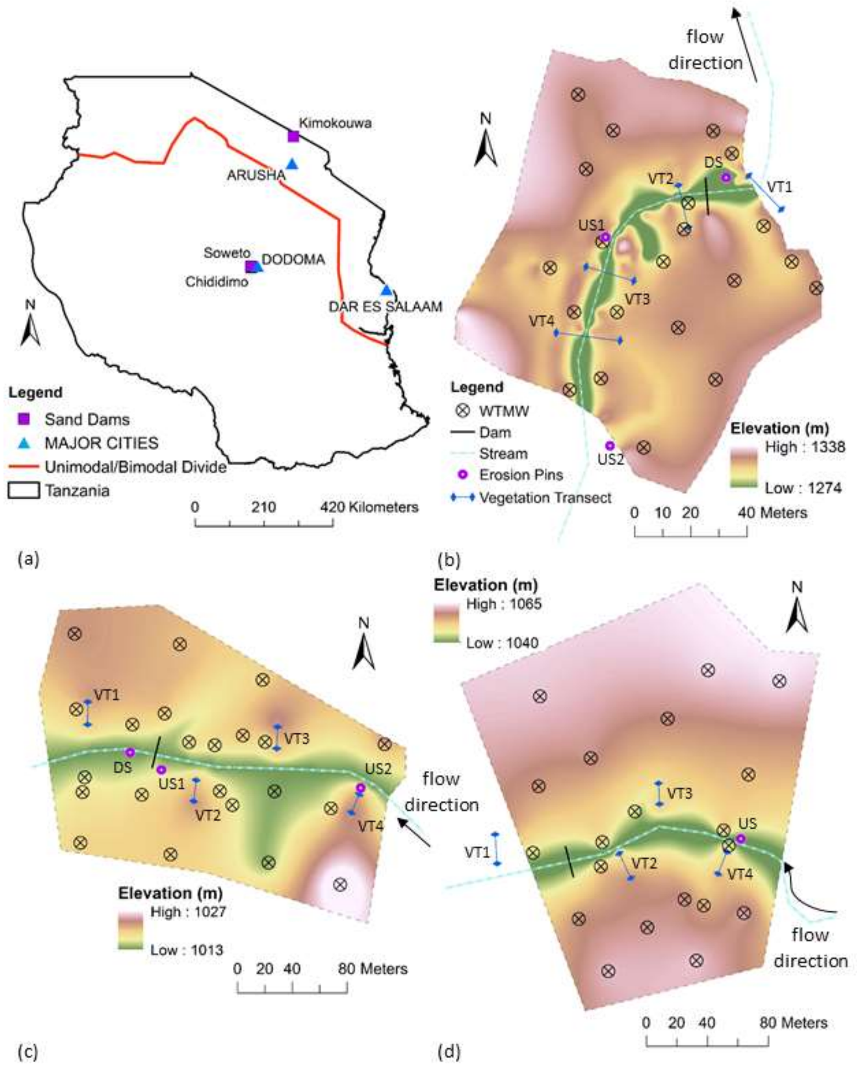


Figure 2: (a) Study Area. The bimodal rainfall region is north of the red line; the unimodal rainfall region is south of the red line (Luhunga and Djolov, 2017); (b) Kimokouwa study area; (c) Soweto study area; (d) Chididimo study area. Elevations are

interpolated from GPS points taken during study. The elevation map includes only the area controlled by the community water groups.

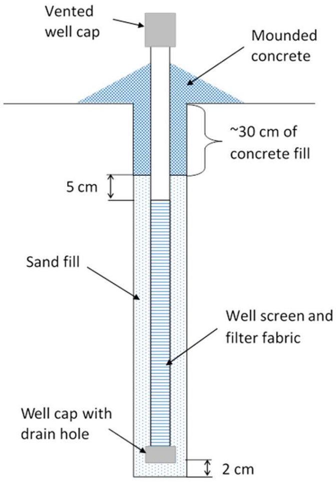


Figure ~~2~~3: Schematic of the water table monitoring wells installed (adapted from Sprecher, 2008).

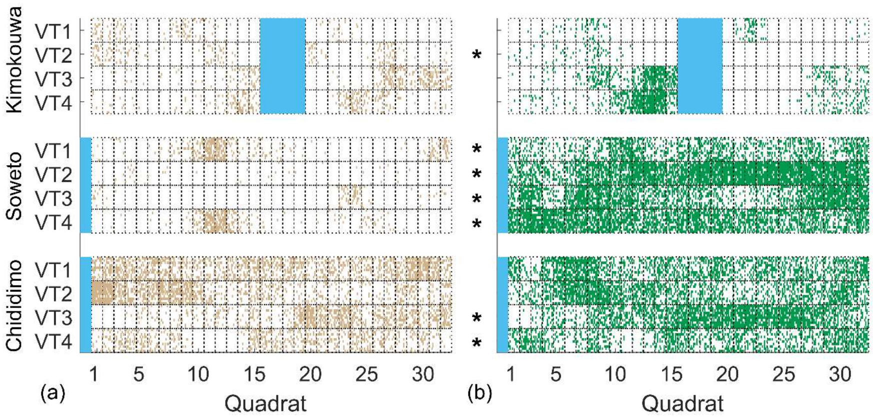


Figure ~~3~~4: Representation of percent vegetative cover for each transect at each sand dam during the (a) dry season and (b) rainy season. The stars indicate a significant difference ($p<0.05$) between the wet and dry season vegetative cover for that transect. The solid colour indicates the location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

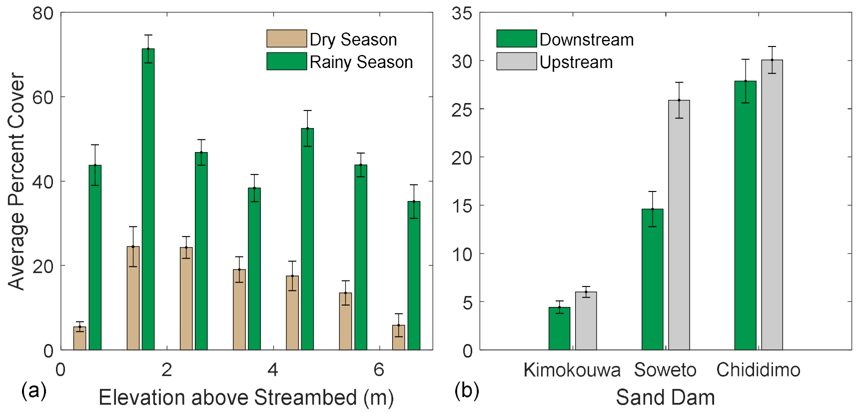


Figure 45: (a) Average percent cover at different elevations above the streambed for the dry and rainy seasons at the Soweto and Chididimo dams. Kimokouwa sand dam was excluded, because the sand dam is not functioning. Standard error bars are shown; (b) Average upstream and downstream vegetative cover at the three sand dams. Standard error bars are shown.

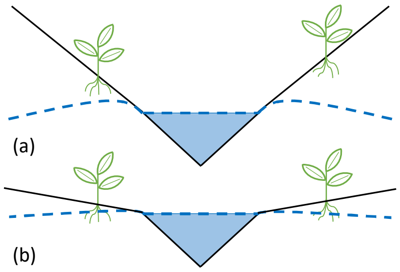
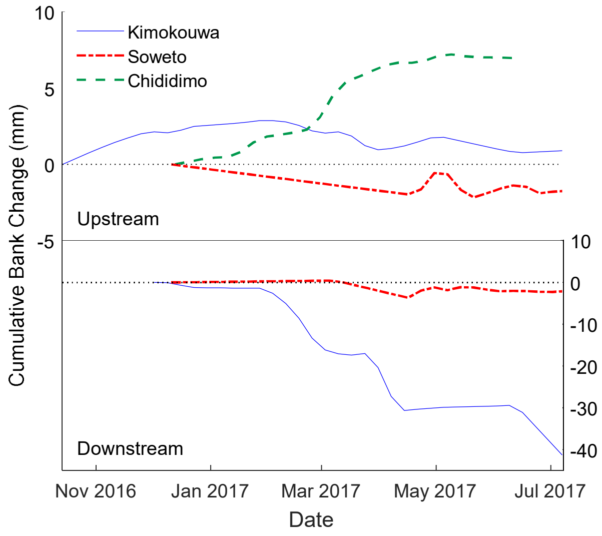
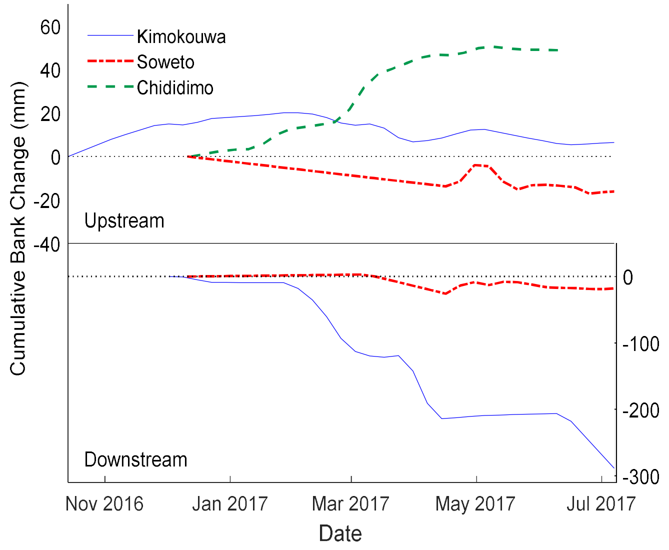


Figure 56: The roots of plants growing on a (a) steep slope will be farther from the locally raised water table created by a sand dam, and therefore have less access to soil water, than vegetation growing on a (b) gentle slope.



Cumulative Bank Change (mm)
10
5
0
-5
Kimokouwa
Soweto
Chididimo
Upstream
Downstream
10
0
-10
-20
-30
-40
Nov 2016
Jan 2017
Mar 2017
May 2017
Jul 2017
Date



Cumulative Bank Change (mm)
60
40
20
0
-20
-40
Kimokouwa
Soweto
Chididimo
Upstream
Downstream
0
-100
-200
-300
Nov 2016
Jan 2017
Mar 2017
May 2017
Jul 2017
Date

Figure ~~6~~7: 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.

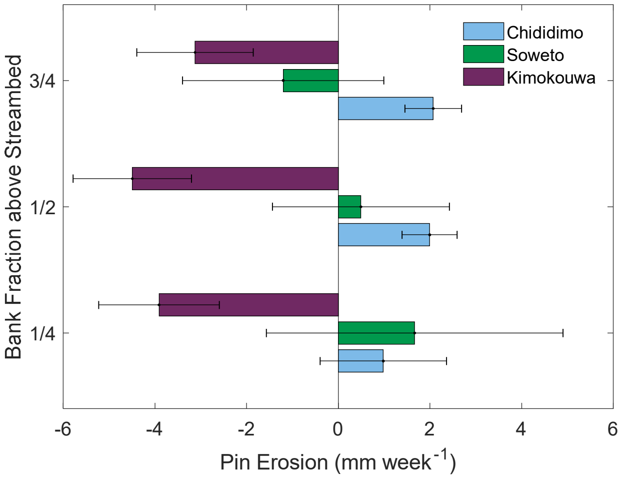
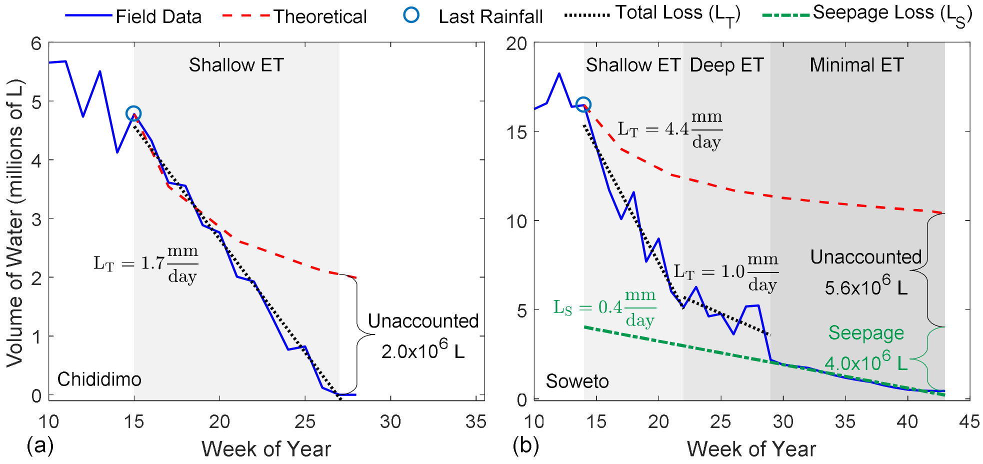


Figure ~~7~~8: Average weekly change in the bank soil at ¼, ½, and ¾ bank height. Positive values represent deposition; negative values represent erosion. Standard error bars are shown.



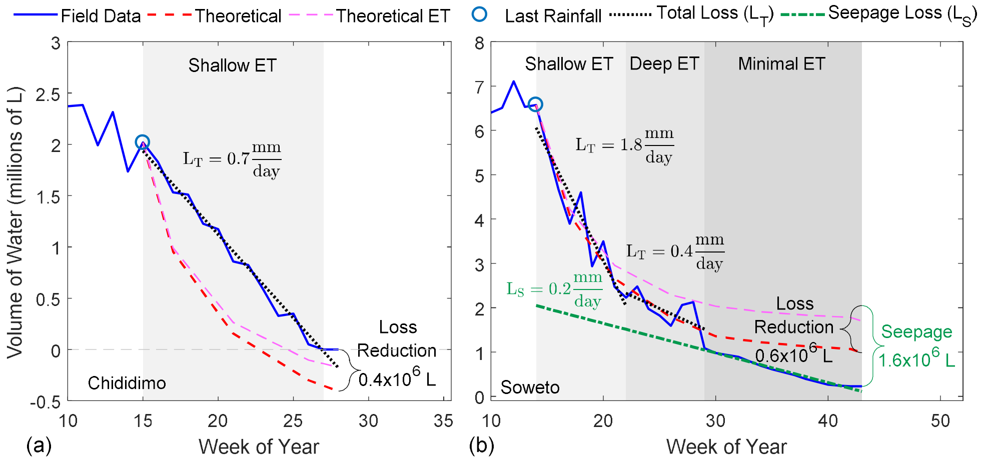


Figure ~~8~~9: Volume of water in the area enclosed by the WTMWs of the (a) Chididimo and (b) Soweto sand dams. The field data line shows the volume of water in the study area during the specified week. The theoretical line, initiated at the end of the rainy season, shows the ~~cumulative~~ theoretical ~~amount~~volume of water in the study area, calculated by integrating ~~equation~~Eq. (1~~).~~) and subtracting from the field-determined volume of water at the end of the rainy season. The theoretical line accounts for losses due to evapotranspiration, baseflow-groundwater runoff, and community use. The theoretical ET line shows the portion of total theoretical loss attributed to ET in the FLDAS dataset.

Table 1: Physical parameters of the three sand dams

Sand Dam	Total width (m)	Total length (m)	Spillway (m)	Estimated storage volume* (m^3)	Wing walls (m)	Spillway height (m)
Kimokouwa	28.78	150	8.74	1310	20.04	2.06
Soweto	23.96	350	16.95	5930	7.01	1.27
Chididimo	22.71	300	9.60	2880	13.11	1.30

**Note:* Storage volume estimated using an average sand dam depth of 2.5 m and porosity of 0.40. The spillway is approximately equal to the width of the stream channel.

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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)		Date installed
									V	H	
Kimokouwa	US1	left	5	3.7	gently sloping	sparse trees and long grasses	silty sand	13	0.9	1	14/10/16
	US2	right	6	5.2	composite		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
Soweto	US1	left	4	2.4	vertical	large bushes and trees	silty sand	12	0.6	1	11/12/16
	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