Response to Reviewer 1

We would like to thank the reviewer for his constructive comments on the manuscript. We have considered the reviewer's comments and provide the following responses.

Statistical Representativeness

5   This study was designed to investigate the claim frequently made by non-scientific bodies that sand dams revitalize the entire ecosystem. This is a claim sometimes repeated, although to a lesser extent, in the introductory sections of sand dam journal articles, but the current body of literature has not tested nor necessarily supported this claim. We do not intend to dismiss the existing sand dam work of various researchers. Rather, we want to challenge the unverified claims about sand dams made by <u>invested</u> parties, primarily NGOs. In having built our study on the

10 foundations laid by the handful of published sand dam studies, we recognize and value the contributions of prior studies. We have altered the language of our primary objective so as to make clear that we are not dismissing the scientific work published to date but rather investigating the claims made by nonscientific bodies.

P2L5-6 has been updated to read: 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

15 *Trincheria et al., 2018; Viducich, 2015).* [A recent publication, de Trincheria et al. (2018) corroborates Viducich's (2015) claim that there are 3000 sand dams, not 1500 sand dams in sub-Saharan Africa.]

P2L20-21 has been updated to read: 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.

20 *P2L24-25 has an additional statement: 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.).*

P2L28-29 has been updated to read: 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

25 *with the local environment.*

We thank the reviewer for drawing our attention to the broad conclusions in the manuscript that were not adequately supported by the discussion and/or strength of the data. In some instances, we agree that the language should be softened to ensure that we do not make claims that cannot be fully backed by the literature and statistical representativeness of the data. We included additional discussion in the manuscript to support some of the

30 conclusions that we believe are justified and adjusted other conclusions to ensure they align with the representativeness of the data collected.

P13L18-20 have been updated to read: 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.

35 *P14L 15-16 has an additional statement: At least one other study, de Trincheria et al. (2015), also recognised the impact of shallow sand reservoirs on water lost to ET.*

Modelling Efforts and Conclusions

An important distinction must be made concerning the motivation for developing a water balance model. The field data of the groundwater levels around the sand dams provide how much water the sand dams are losing over time. The model is being employed to inform the estimate of the various *causes* of those losses. This distinction was clarified in the article.

P6L27-28 has been updated to read: To help determine the various causes of water loss from the sand dam and their relative magnitude, a water balance was calculated …

The reviewer's issues with the model are addressed by number.

1. **The model calculates Qout based on the other terms, it therefore accumulates all errors in Qout, including errors because of terms not included in the model**
   There is uncertainty in the model, because the water balance is a simplified representation and the forcing data (FLDAS) is largely modelled data itself. Despite the uncertainty, the authors are confident that the relative magnitude of the terms in the model is reliable. The relative magnitude of the terms is the primary focus of the conclusions drawn from the model. We added an explicit statement noting the uncertainty in the model.

   P7L6-9 has an additional statement: 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.

2. **I assume from figure 7 that the authors start the dams "full". This is not made explicit in the article.**
   The analysis displayed in Figure 7 begins in the middle of the rainy season, so it is assumed that the sand dams are full at this point. However, this will change as a result of our model changes resulting from point 3, below. A sentence indicating the initial condition of the model was added to the manuscript.

   P7L1 has been updated to read: $Q_{out,dry\ season}$ is the rate of water loss from the sand dam after the end of the rainy season…

   P7L3-5 has been updated to read: Eq. (1) is integrated over time and subtracted from the volume of water in the control volume at the end of the rainy season to create a theoretical volume of water curve for the sand dam area.

   Figure 7 (now Figure 8) caption has been updated to read: The theoretical line, initiated at the end of the rainy season, shows the cumulative theoretical amount of water in the study area…

3. **The inflow term 0.038CP(t) accounts (I think, not made clear) for the amount of rain water that falls on the dam itself and is subsequently stored? I would argue that during a rain event all water from upstream would be routed over the stream-bed thus re-filling it. The 0.038 term from Aerts 2007**

relates to the total amount of water a sand dam saves from annual discharge to see if dams have an impact on downstream water availability. This factor cannot be used as the authors do.

You are correct. The 0.038 term, hereafter capture ratio, from Aerts (2007) is the maximum proportion of annual discharge that a sand dam is expected to capture and store. In the water balance model proposed in the manuscript, the inflow term, $0.038CP(t)$, accounts only for the runoff that is expected to occur from the study areas indicated in manuscript Figure 1c,d. The area included in the model, therefore, is greater than the dam itself, but smaller than the upstream watershed. The watershed upstream of the Chididimo sand dam is 3.3 km^2 and relatively uniform. This allows the watershed to be modelled relatively well using the rational method for overland flow with a capture ratio of 0.038. The watershed upstream of the Soweto sand dam, however, is 262.1 km^2 and includes commercial farmland and an 18.6 km^2 wetland area. The Soweto sand dam is much too small to capture 0.038 of the runoff generated by such a large watershed. To more accurately represent the volume of water captured by the Soweto sand dam, the capture ratio would need to be reduced to around 0.00025 and adjusted for seasonal variability. However, such a methodology seems somewhat speculative, and we would prefer to be consistent in our methodology. In summary, the inflow term proposed in the water balance model is insufficient for accurately representing the volume of water captured by the Soweto sand dam. To address this issue, we initialized the water balance at the week of last rainfall. Therefore, there are no inflows to the theoretical model. The model now solely describes the loss factors, which is our primary interest (see Eq. 1 and Fig. 3, below).

4. **The 0.15 factor from Kumar 2018 relates to the percentage of evap that is canopy evap in the Noah LSM, which, if I recall correctly, was not calibrated for the region that the authors use it for. I would guess that on the African regions of interest here, the amount of canopy versus other evap would be different.**

While the Noah LSM may not have been calibrated for East Africa, there are examples of Noah LSM being used over East Africa (Anderson et al., 2012; Yilmaz et al., 2014). Further, the evapotranspiration (ET) data used in the theoretical model presented in this paper is from FLDAS. The iteration of FLDAS used was developed based on the Noah LSM, but is specifically designed for use in sub-Saharan Africa (McNally et al., 2017). Furthermore, we believe the 0.15 factor for ET partitioning described in Kumar et al. (2018) to be appropriate. The climate in Dodoma, Tanzania is classified as hot semi-arid, which is also the climate in parts of the southwestern US and northern Mexico. From the figure below, included in the Kumar et al. (2018) paper, you can see that the canopy ET partition fraction for much of the southwestern US and northern Mexico falls between 0.1 and 0.2.
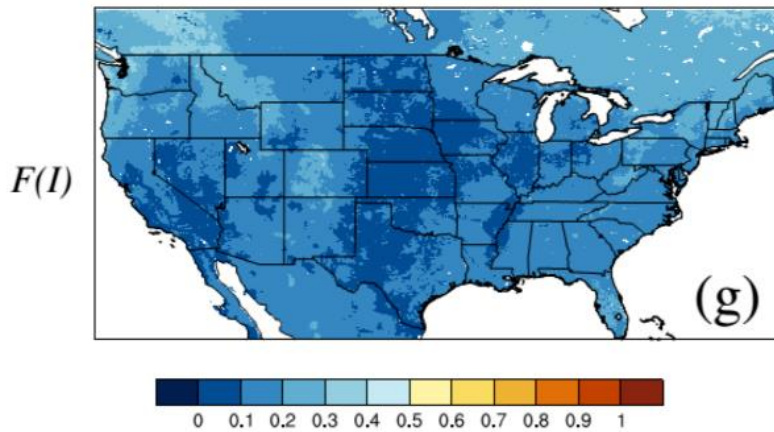
Figure 1: Mean of the ET partition fraction of canopy ET (unitless; from Kumar et al., 2018).

We recognize that the 0.15 ET partition fraction may not be perfectly accurate, but a study such as Kumar et al. (2018) has not been performed for East Africa. There is no better estimate available.

To more accurately represent the amount of water lost to ET within the control volumes, the ET will be multiplied by a factor of 0.85 for the area within the sand dams and will be multiplied by a factor of 1 outside of the sand dams. There is potential canopy ET outside the sand dams but within the control volume.

P7L1-2 has been updated to read: 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.

P7L15-16 has been updated to read: Therefore, total evapotranspiration is reduced by 15 % in Eq. (1) for the portion of the control volume that is occupied by the sand dam.

In addition, we realize that our manuscript is not clear on the size of the control volume to which the theoretical model is applied. Figure 2, below, provides the control volume for the Chididimo and Soweto sand dams. The control volume includes the sand dam and all area enclosed by the water table monitoring wells (WTMW) installed around the study area. Figure 2 was not added to the manuscript, but a statement clarifying the extent of the control volumes was added.
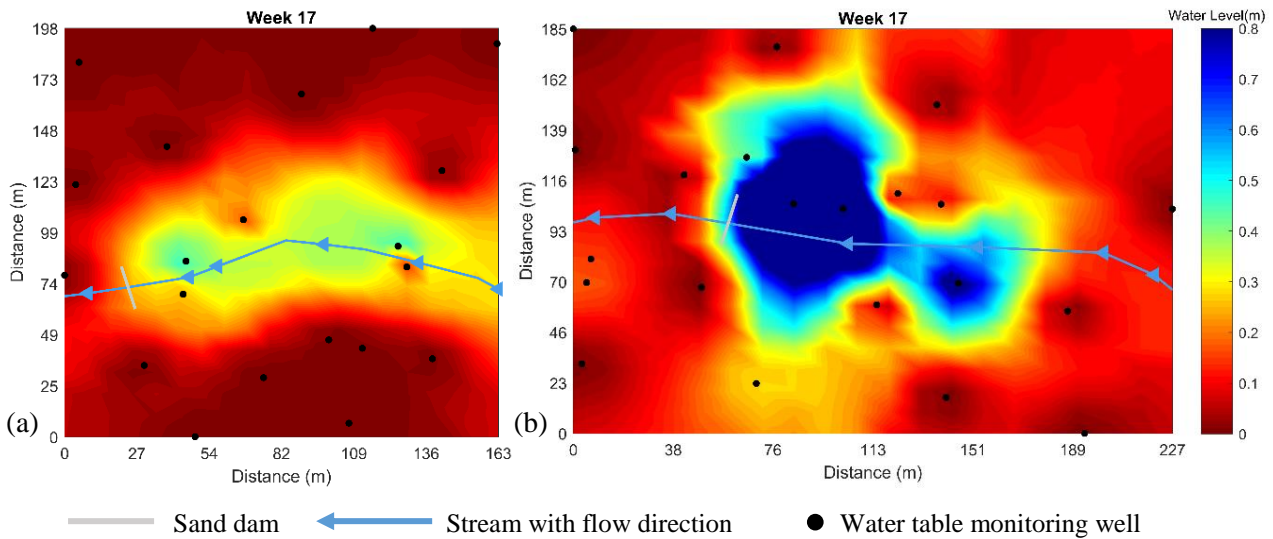
Figure 2: Height of subsurface water around the (a) Chididimo sand dam and the (b) Soweto sand dam.

P7L5-6 has an additional statement: The control volume to which Eq. (1) is applied is the portion of the study area that is enclosed by the installed WTMWs (see Fig. 1 c,d). For Chididimo, this area is 32 274 m², while it is 41 995 m² for Soweto.

5. **The Qcomm term is estimated based on conversation with locals. This is understandable given the constraints of the research, but introduces a very large uncertainty. In my own research we observed that some people living close to the dam would, against the deal with the entire community, use a machine pump to irrigate their lands from the sand reservoir, draining the reservoir very fast (Hut 2008).**

We appreciate and understand the concern regarding the uncertainty of the community withdrawals variable. We added a sentence to the manuscript indicating that the estimate of community withdrawals has an unknown degree of uncertainty. We, however, have no reason to believe that the community members were engaging in machine pumping of the water. The Soweto sand dam did have many areas under cultivation near the dam, but we did not see any evidence of machine pumping. Also, the community water group was very strict with its members regarding withdrawals under the guidance of the local chairman, including such measures as locking access to the hand pump. The Chididimo sand dam was much more difficult to access, and only had one small area nearby under cultivation. These reasons coupled with the lack of evidence lead us to believe that machine pumping was not a significant factor in the rate of water loss in the Soweto and Chididimo sand dams.

P7L17-20 has an additional statement: The estimate of the community's use of water from the sand dam 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.

5

Given the above, Eq. (1) was modified to:

P6L32-P7L5:

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

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. (1) is integrated over time and subtracted from the volume of water in the control volume at the end of the rainy season to create a theoretical volume of water curve for the sand dam area.

Given the changes to Eq. (1), Figure 7 (now Figure 8 in manuscript) was modified to:
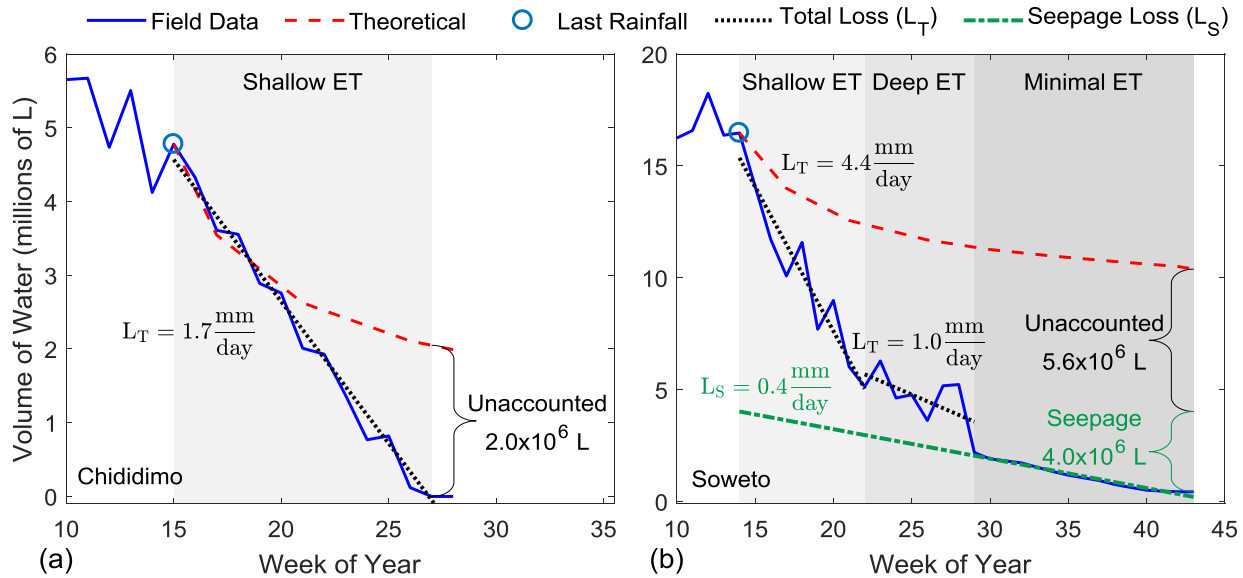
Figure 3: Volume of water in the area enclosed by the WTMWs of the (a) Chididimo and (b) Soweto sand dams. The field data line shows the volume of water in the study area during the specified week. The theoretical line, initiated at the end of the rainy season, shows the theoretical amount of water in the study areas, calculated by integrating equation (1). The theoretical line accounts for losses due to evapotranspiration, baseflow-groundwater runoff, and community use.

The changes to Eq. (1) result in the following loss partitioning (summary of changes, not for inclusion in manuscript):

Table 1: Sand dam stored water loss partitioning during the dry season

Loss Partition (%)	Chididimo		Soweto	
	Old Eq. (1)	Updated Eq. (1)	Old Eq. (1)	Updated Eq. (1)
Evapotranspiration	85	53	51	35
Baseflow-groundwater runoff	1	1	1	1

Community use	5	4	8	4
Seepage	-	-	-	25
Unaccounted	9	42	40	35

From Table 1, above, you can see that the loss partitioning for the Chididimo sand dam did not change much as a result of updating Eq. (1), with the exception of the unaccounted fraction which is still understood to be primarily ET losses. The loss partitioning for the Soweto sand dam did change significantly with the inclusion of seepage losses. The Soweto sand dam does lose water as a result of seepage, as evidenced by the scoopholes community members dig just downstream of the dam from which they collect water. Community members did not exhibit the same behavior at the Chididimo sand dam, therefore we do not believe that there is significant seepage occurring at the Chididimo sand dam. At Soweto, the community members expressed an inability to abstract water from the sand dam after approximately the 30th week of the year. Therefore, we believe that the water lost from the Soweto sand dam after the 30th week is likely due primarily to seepage losses. Assuming seepage is relatively constant, we can extrapolate this portion of the plot back to the end of the rainy season and get an estimate of total seepage losses from the Soweto sand dam during the dry season (Fig. 3b). There is likely minimal ET loss occurring after the 30th week, because the water is deep underground at that point (Hellwig, 1973).

P12L4-P12L13 now reads: The Soweto dam exhibits three distinct phases of water loss: shallow ET, deep ET, and minimal ET (see Fig. 8b). 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). 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 mm day^{-1} and accounts for 25 % 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 essentially remains constant throughout the shallow and deep ET phases (see Fig. 8b). Having accounted for seepage, the remaining 35 % unaccounted water loss at Soweto is likely lost primarily due to ET.

In regards to your estimate of the mm/day rate of evapotranspiration from the sand dams, the estimate is quite high due to the misunderstanding about the size of the control volume from which the field data line is determined for Figure 3. From Figure 2, above, there is clearly a great deal of seepage from the sand dam through the streambanks, so the area from which evapotranspiration is occurring is significantly greater than simply the surface area of the sand dams. The updated estimates for the rate of evapotranspiration losses from the Chididimo and Soweto sand dams are: 380 000 L/week and 1 117 000 L/week (slope of total loss-seepage loss, Fig. 3), respectively. With this understanding, the rate of evapotranspiration losses can be calculated as follows:

$$Total\ Loss\ Rate(L_T)\frac{mm}{day} = \frac{Slope\ of\ Total\ Loss\ Line\ \frac{L}{week}}{7\frac{days}{week} \times Control\ Area\ (m^2)}$$

$$Avg.Evap\ Rate\left(\frac{mm}{day}\right) = Total\ Loss\ Rate\frac{mm}{day} \times (Evap + Unaccounted\ Fraction)$$

$$Avg.\,Evap\,Rate_{Chididimo,shallow}\left(\frac{mm}{day}\right)=\frac{380\,000\,\frac{L}{week}\times(0.53+0.42)}{7\,\frac{days}{week}\times(163\,m\times198\,m)}=1.56\,\frac{mm}{day}$$

$$Avg.\,Evap\,Rate_{Soweto,shallow}\left(\frac{mm}{day}\right)=\frac{1\,300\,000\,\frac{L}{week}\times(0.35+0.35)}{7\,\frac{days}{week}\times(227\,m\times185\,m)}=3.09\,\frac{mm}{day}$$

The above evapotranspiration rates are in general agreement with the sand dam sub-surface evaporation rate of 2.4 mm/day found by Borst and de Haas (2006). It should also be noted that the Soweto estimate is valid only for the rate of ET when the sand dam is relatively full. As is clear in Figs. 3b and 4b, the rate of ET decreases as the volume of water in the sand dam decreases.

Response to Reviewer 2

We would like to thank the reviewer for the constructive comments on the manuscript. We have considered the reviewer's comments and provide the following responses.

It is therefore a bit disappointing that only three dams are considered in this study, and also that there is no attempt to understand the communities' perceptions of the sand dams.

This study's success relied on active participation of community water groups to help collect long-term datasets. Of the 15 sand dams in Tanzania known to us, only three still have active community water groups maintaining the dams. This, in addition to funding limitations and long travel times, prevented us from performing in-depth field studies for more than three sand dams.

We worked very closely with the community water groups over the course of the study and developed a good understanding of their perception of their sand dam. From day one, the communities expressed frustration that the sand dams did not serve as a water source throughout the dry season. One community, Soweto, went so far as to lock the handpump at the sand dam to limit easy access to the water. However, the social aspect of sand dams is not the focus of this study, so any related commentary has been omitted.

I am curious as to why FLDAS is selected, there is no justification.

FLDAS was selected as a proxy for climate data, because there is not a consistently reliable source of climate data available for Dodoma or Longido, Tanzania. FLDAS is not the perfect substitute, but it has been specifically designed and validated for use in sub-Saharan Africa. A line was added to the manuscript explaining the choice of the FLDAS dataset.

P6L29-30 now contains the following statement: 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.

It seems to assume that all water loss must be through evaporation rather than considering that there may be leakage from the trapped sand, either under the dam wall or through the riverbed. This could help explain some of the results (e.g. p. 8 line 16-18, p. 10 lines 1-4, p. 10 line 10, p. 10 line 20-21. p. 11 line 2, p. 12 line 16,

p. 12 line 19) and would have a big impact on the conclusions. The established literature on evaporation is only referenced right at the end of the discussion (p. 12 line 25).

Based on the relative magnitude of loss terms in Eq. (1) in the manuscript and the prolonged availability of near-surface water resulting from storage in the sand dam, we believe that most of the unaccounted losses are due to evapotranspiration at the Chididimo sand dam. However, we have considered the comments of Reviewer 1, and updated our conclusions regarding water loss at the Soweto sand dam. Unlike the Chididimo sand dam, the Soweto sand dam did exhibit signs of seepage under the dam wall. We added a statement to the manuscript acknowledging that seepage through the streambed could be contributing to the unaccounted water loss.

P11L18-19 has been updated to read: The unaccounted water loss could be due to seepage through the streambanks or streambed or possibly a higher rate of ET than simulated by FLDAS.

P11L34-P12L2 has been updated to read: The unaccounted water loss could be due to seepage under the sand dam wall, through the streambanks, or streambed or possibly a higher rate of ET than simulated by FLDAS.

P11L23-27 now reads: 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). Seepage could be contributing to the total loss rate at Chididimo. There was no evidence of seepage under the dam wall, however, seepage through the streambed could impact the total loss rate at Chididimo.

In order to calculate the storage in the sand dam (p.6 line 30-31), why not just assume that it is fully saturated at the end of the wet season? This could be supported if you observe water ponded on top of the trapped sand.

Thank you for your suggestion. In response to comments from Reviewer 1, we have updated Eq. (1) and initiated the theoretical water loss model at the end of the rainy season. This was updated in the manuscript.

I am curious as to why the WTMWs were the only attempt to measure water levels the sand dams. Piezometers or even excavated holes in the sand dam could have provided a more comprehensive picture. In my experience observing the water depth in scoop holes that the communities dig can be an excellent indicator of overall water levels, but I don't know if there were present here.

Borst and de Haas (2006) installed piezometers in the sand dam itself, so we did not think it necessary to repeat this arrangement. Instead, we wanted to focus on how the sand dam affects the water table outside of the stream channel, since the idea that sand dams raise the local groundwater table has really only been explored via modelling (Hut et al., 2008; Quilis et al., 2009). Therefore, we installed WTMWs in the streambanks and the surrounding area to track how the water table was changing over time. We did not consider tracking water levels in the scoop holes dug by community members but will consider this as a viable methodology for future studies.

I am also not surprised by the results of the macroinvertebrate study. That a dry river bed in an arid region contains no macro invertebrates seems hardly to be a surprise. This methodology seems to be more suited to perennial rivers.

Boulton et al. (1992), Stubbington et al. (2009), and Verdonschot et al. (2014) all successfully used variations of the methodology described in the manuscript to sample dry river beds. Boulton et al. (1992) even sampled an

ephemeral river in the Arizona desert. We believe that we used the appropriate methodology for collecting macroinvertebrates from an ephemeral streambed. If sand dams were less homogeneous and therefore more suitable habitats for macroinvertebrates, we believe we would have been successful in our sampling attempts.

Macroinvertebrate sampling in perennial rivers is most often conducted by placing a net, typically a surber sampler, facing upstream on the streambed and then disturbing the upstream streambed to release any macroinvertebrates nestled there. The flowing stream then carries the macroinvertebrates into the net, where they are captured and identified.

There are results on the sediment grain size (p 7 line 19) but no methodology to measure it.

A formal sediment grain size analysis was not performed. A statement was added to the manuscript to clarify this point.

P8L6-7 has been updated to read: 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.

p. 8 line 4 – I am struggling to see how the vegetated cover is correlated to the land slope in figure 3. Could this be confirmed through a statistical test?

The paragraph immediately preceding (p. 7 line 25-p.8 line 2) discusses the relationship between land slope and vegetated cover in the context of Figure 3. This relationship is not immediately apparent from the figure alone. The statement on p. 8 line 4 was edited to reduce the chance for reader confusion, and Pearson's Correlation Coefficient has been calculated and added to the discussion to validate the claim.

P8L21-27 has been updated to read: 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 (ρ=-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 (ρ=0.04), which is expected because the sand dam is not contributing to a locally raised water table.

p. 8 line 8-9 – point 1 is poorly explained, and again on p. 11 line 29-32. A figure would help here.

Figure 5, below, was added to the manuscript to help clarify the point. In addition, further discussion of how flat land can generally support more vegetation than steeply sloping land was added to the manuscript. Shemsanga et al. (2018) was added to the manuscript in support of using healthy vegetated cover as an indication of groundwater in Dodoma.
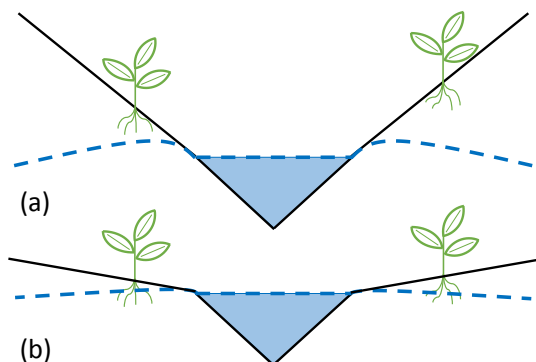
Figure 5: The roots of plants growing on a (a) steep slope will be farther from the locally raised water table created by a sand dam, and therefore have less access to soil water, than vegetation growing on a (b) gentle slope.

5 *P8L32-P9L4 have been updated to read: 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). 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.*

10 *P9L7-15 contain a new paragraph: 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). 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*
15 *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.*

20 **p. 9 line 21-25 – this is hard to follow.**

These lines were updated to remove unnecessary detail and clarify the point.

P10L23-26 have been updated to read: 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, the community is unable to use the sand dam as a source of domestic water. Silt layers formed at
25 *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).*

p. 9 line 24 – how can soil be assessed properly in advance to avoid this type of failure?

A statement with this information was be added to the manuscript.

P10L26-29 has the following statement added: 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.

5 **p.10 line 31 – by "subsurface water reservoir" do you mean the underlying aquifer of the trapped sand?**

Yes, we mean the water stored between the grains of sand in the sand dam. The wording of this statement has been altered to reduce reader confusion.

P12L17-18 have been updated to read: However, the dataset does not account for the additional water available in the perched aquifer created by the sand dam's stored water.

10 **p. 12 line 6 – please be more specific on why the stream channel migration is important.**

Noted. We added a few sentences to the manuscript explaining how increased erosion and stream channel migration can lead to the failure of a sand dam.

P13L26-27 has an additional statement: 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
15 *washed downstream.*

Response to Reviewer 3

We would like to thank the reviewer for the constructive comments on the manuscript. We have considered the reviewer's comments and provide the following responses.

20 **1. An important area of research - I don't think the impact of sand dams on invertebrates has been studied before and there is much that we don't know about such a popular technology in general. The authors are right to ask questions and I would like to see more, more rigorous research.**

Thank you. We hope this first foray into studying a sand dam's impact on macroinvertebrates leads to further research on the topic and, generally, on macroinvertebrates in semi-arid, ephemeral streams.

25 **2. My main feedback relates to the main claim that sand dams are detrimental to macro invertebrates. In order to make this assertion I would have expected to see some sort of comparative study between river beds that are suitable for sand dams but where sand dams have not been built, vs. river beds with sand dams.**

The manuscript is careful to not claim that sand dams are detrimental to macroinvertebrates, because the study did not include legitimate control sites due to limitations in implementing the planned research. Rather, the manuscripts
30 uses the phrasing that sand dams "are not suitable habitats" for macroinvertebrates. This was explicitly clarified in the manuscript.

P7L25-28 has an additional statement: 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
35 *compare macroinvertebrate assemblages in undammed sandy riverbeds with those in sand dams.*

3. I would not expect to see a great deal of macro invertebrates in a semi arid dry riverbed, if sand dam levels are not 'normal', what level are they comparing it to?

We believe this point is answered by our response to point number 2, above.

4. The authors claim a lack of quantitative research skews perceptions towards a rosier picture of sand dams than is true, but their study has a small sample size, over only one season (although intensively studied). There were probably practical limitations - research is expensive, but this could be acknowledged.

Thank you for noting this point. We added a statement acknowledging the limits of our study.

P2L 29-32 now has an additional statement: The study is limited to only three sand dams, because the study design relies on the active participation of local community water groups. Most of the community water groups formed during sand dam construction had disbanded 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.

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

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Abstract. Sand dams, a popular water harvesting structure employed by rural communities, capture and store water for use during the dry season in arid and semi-arid regions. Most sand dam research has been performed on the "ideal" sand dam, despite approximately fifty percent of sand dams not functioning as intended. This research involves a year-long, in-depth field study of three sand dams in Tanzania, one of which is essentially non-functioning. The study investigated a sand dam's

10   impact on macroinvertebrate habitat, vegetation, streambank erosion, and the local water table. Surveys of macroinvertebrate assemblage were performed each season. Vegetation surveys were performed every other month, and erosion was recorded semi-monthly. Water table monitoring wells were installed at each sand dam, and measurements were taken twice a day. The study showed that sand dams are not a suitable habitat for macroinvertebrates. The non-functioning sand dam has a thick layer of silt preventing infiltration of rainwater. The functioning sand dams store a significant amount of water, but most is lost to

15   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

20   International development projects in the Global South are managed by either a national department, private company, non-governmental organization (NGO), or a group of international development agencies (Ika, 2012). Success metrics for international development projects are typically defined by the funding organization, which are most often multilateral or bilateral organizations (e.g. the World Bank, United States Agency for International Development, etc.) or individual donors (Ika, 2012). Unfortunately, project success metrics frequently only tell one side of the story, focusing on financial and technical

25   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

30   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).

5

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

10 explored how sand dams impact the local water table (Hoogmoed, 2007; Quilis et al., 2009). Other studies used modelling to further explore the seepage of sand dam water through streambanks (Hut et al., 2008) and the potential of sand dams to increase water security in Ethiopia (Lasage et al., 2015). The socio-economic benefits of sand dams has also been explored (Lasage et al., 2008) along with the negative effects of sand dam siltation and/or seepage due to poor construction and or siting (Nissen-Petersen, 2006; de Trincheria et al., 2015; Viducich, 2015). Except for the Borst and de Haas (2006) study on the ideal sand

15 dam, most published sand dam studies are based on survey data or modelling efforts. Published studies do not tell the whole story of sand dam impacts, and this has created a false perception of the risks involved with sand dam construction.

This study 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. Specifically, the study

20 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 sand dams alter the groundwater table in the surrounding area? 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

25 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 of the community water groups formed during sand dam construction had disbanded at the time of this study.

30 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; Luhunga and Djolov, 2017). Tanzania is fairly flat, with the exception of the highlands on the southern border and, of course, Mount Kilimanjaro to the east of Arusha. There are at least 15 sand dams in Tanzania, three of which will serve as study sites for this research (see Fig. 1a). Most of the sand dams were funded by the Mennonite Central Committee of Tanzania (MCC) and designed by Kenya-based NGOs. Dodoma has nine sand dams; Longido, a small town near the Kimokouwa sand dam (see Fig. 1a), has four sand dams, and there are a few sand dams elsewhere in the country.

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

2.1 Kimokouwa sand dam

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

2.2 Soweto sand dam

The Soweto sand dam (see Fig. 1c) is located approximately 20 km west of Dodoma, Tanzania's capital city. Construction of the sand dam was completed in June 2011 with funding provided by MCC and design and construction expertise provided by the Sahelian Solutions Foundation of Kenya. A hand pump was installed near the sand dam at the time of dam construction. The Soweto site is the flattest of the three sand dam sites, with an elevation change of only 14 m across the site. The

streambanks are quite flat near the dam, and the community is able to grow many crops on the banks, using water from the sand dam to irrigate the crops. At 17 m wide, the stream at Soweto is also the widest of the three sand dam sites.

2.3 Chididimo sand dam

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

3 Data Collection and Analysis

3.1 Community water groups

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

3.2 Macroinvertebrate survey

Macroinvertebrate surveys performed at each site were intended to serve as an indication of water quality and overall habitat health. At each sand dam, samples were extracted at two locations upstream of the dam and one location downstream of the dam. All samples were taken from the middle of the streambed. During the dry season, a 25 cm x 25 cm by 10 cm-deep hole was dug in the streambed with a small shovel, and the extracted bed material was transferred to a plastic bucket (Verdonschot et al., 2014). Holes drilled in the bucket's lid were plugged with cotton to prevent transfer of macroinvertebrates into or out of the sample (Stubbington et al., 2009). The samples were transported to the research base and rehydrated with de-chlorinated water to encourage re-emergence of desiccation-tolerant life stages (Boulton et al., 1992; Stubbington et al., 2009). For a 28 day period, the samples were checked daily for macroinvertebrates. During the 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 b,c). At Kimokouwa, where the stream is narrow, the centre of each transect lay at the middle of the stream (see Fig. 1d).

3.4 Erosion study

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

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

3.5 Water table monitoring

Water table monitoring wells (WTMW) were installed at each sand dam to track changes in the water table over time. A drilling team hand-augured boreholes 10 cm in diameter at 63 locations across the three sites (see Table 3). For each WTMW,

the drilling team continued drilling until the team encountered hard rock or another material prohibiting the progress of the auger. A WTMW was installed only if a hole deeper than 0.5 m was achieved. A soil log was completed for each WTMW noting the soil depth, texture, colour, wetness, and cohesion for each horizon. See Fig. 1b-d for WTMW layout at the sand dams. Fig. 2 provides a schematic of the WTMWs. The WTMWs installed were schedule 40 polyvinyl chloride pipe 32 mm

5   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

10   Fig. 2).

Volunteers from the community water groups took measurements of the water table every morning and evening during the rainy season after the WTMWs were installed. After the wells dried up, measurements were taken less frequently—approximately once a week. The water table measurements were taken by slowly lowering a Solinst® Model 101B Basic

15   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

20   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.

25   Of the three sand dams studied, the Chididimo data provides the best picture of how the water table fluctuates near a sand dam.

The water table measurements were used to determine the volume of water in the sand dam and riparian zone over time. To help determine the various causes of water loss from the sand dam and their relative magnitude, a water balance was calculated using data from Famine Early Warning Systems Network Land Data Assimilation System (FLDAS). FLDAS data was used

30   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:

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

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. (1) is integrated over time and subtracted from the volume of water in the control volume at the end of the rainy season to create a theoretical volume of water curve for the sand

5 dam area. The control volume to which Eq. (1) is applied is the portion of the study area that is enclosed by the installed WTMWs (see Fig. 1 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.

10

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 will not lose water due to evaporation of canopy-intercepted rainfall, so 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

15 Models, which are incorporated into FLDAS (McNally et al., 2017). Therefore, total evapotranspiration is reduced by 15 % in Eq. (1) for the portion of the control volume that is occupied by the sand dam. 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 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

20 Dodoma site to indicate the community was drawing significantly more water from the sand dams than they indicated.

4 Sand dam impact

4.1 Macroinvertebrates

The various macroinvertebrate survey trials produced only one specimen—at Kimokouwa during the dry season. This failure to produce macroinvertebrates indicates that sand dams are not a suitable habitat for macroinvertebrates during any season of

25 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 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

30 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).

5   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

10   largely explain the absence of macroinvertebrates in the sand dams.

4.2 Vegetation

The vegetative cover at the three sand dams differed greatly throughout the study (see Fig. 3). Kimokouwa, unsurprisingly, had the lowest level of vegetative cover overall and did not 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.

15   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), 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.

20

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

25   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

30   and the dry season (see Fig. 4a). 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. 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). The raised water table has a positive impact on the soil moisture

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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 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). 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). 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, 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 support more vegetation, because of the additional stored water that is available to vegetation for use in transpiration.

4.3 Streambank erosion

The temporal changes in the bank soil varied somewhat across the three sand dams (see Fig. 6). 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 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).

5　The spatial changes in bank soil also vary between the three sand dam sites (see Fig. 7). 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

10　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,

15　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

20　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).

4.4 Water Table

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, the community is unable to use the sand dam as a

25　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.

30　Siltation of a sand dam occurs during rainfall events prior to the sand dam's maturation, or before the sand reservoir has naturally reached the height of the spillway. Sand dams in areas with silty sand should be constructed in thirty cm stages to ensure that the portion of the water column with suspended silt flows over the spillway instead of settling behind an immature sand dam (Nissen-Petersen, 2006).

A functioning sand dam typically fills with water after one high intensity rainfall event and remains essentially full throughout the rainy season (Ertsen and Hut, 2009). The stored water seeps into the banks, raising the water table in the riparian zone. The last rainfall of the season at Chididimo and Soweto occurred around early to mid-April, approximately the fourteenth or fifteenth week of the year. Fig. 8a 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). 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 % 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 % of the total water lost during the dry season attributed to baseflow-groundwater runoff and 42% unaccounted, ET was responsible for at least 53 % of the water lost from the Chididimo sand dam according to FLDAS data and Eq. (1) (see Fig. 8a). The unaccounted water loss could be due to seepage through the streambanks or streambed or possibly a higher rate of ET than 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 water is likely lost due to ET (see Fig. 8a). 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). Seepage could be contributing to the total loss rate at Chididimo. While there was no evidence of seepage under the dam wall, 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 % 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 % unaccounted, ET was responsible for at least 35 % of the water lost from the Soweto sand dam according to Eq. (1) (see Fig. 8b). The unaccounted water loss could be due to

seepage under the sand dam wall, through the streambanks, or streambed or possibly a higher 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). 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). 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 mm day^{-1} and accounts for 25 % 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). Having accounted for seepage, the remaining 35 % unaccounted water loss at Soweto is likely lost primarily due to ET.

Fig. 8 shows that the sand dams lost water at a faster 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. 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 1.7 mm day^{-1} and 4.4 mm day^{-1}, respectively. This high rate of ET means that the sand dams can no longer provide water to the community after the months of July or August in most years.

The Soweto sand dam is losing water during the shallow ET phase at nearly 2.5 times the rate of the Chididimo sand dam. 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 and higher rates of ET than a typical sand dam in Kenya experiences (NASA/GSFC/HSL, 2016). Sand dams are intended to protect the stored water from evaporation, but the ground surface is inadequate protection against the high temperatures and dry air at the Chididimo and Soweto sand dams.

5 Discussion of impacts and recommendations

5   The impact of a sand dam depends not only on its dimensions and construction but also on features of the surrounding land and the management of the dam's water resource by the local community. The field study revealed that a non-functioning sand dam might significantly influence streambank erosion but has little impact on the local water table and vegetation. The functioning sand dams, however, had little impact on streambank erosion, significant impact on the local water table, and varied impact on vegetation. Regardless of a sand dam's functionality, none of the sand dams in the study were a suitable

10   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

15   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). 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

20   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

25   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.

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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

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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
5   average higher rates of ET than the annual rainfall and average ET at the Kenyan sand dams. Less rainfall 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 sand dams help slow the rate of ET, ET is still the greatest loss factor for the stored water. Chididimo has a shallower sand dam and lost at least 53 % of its
10   stored water to ET, while Soweto is deeper and lost at least 35 % 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). To help reduce the amount of water lost
15   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

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
20   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
25   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.

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.

5 **Author contribution**

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

Competing interests

The authors declare that they have no conflict of interest.

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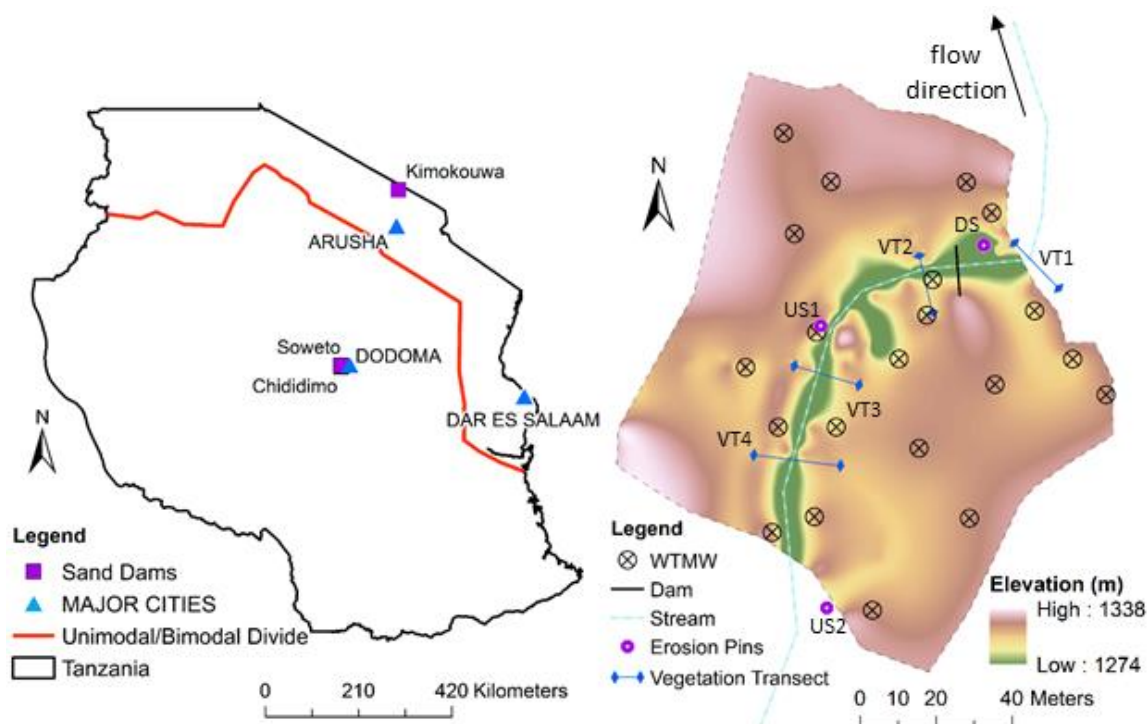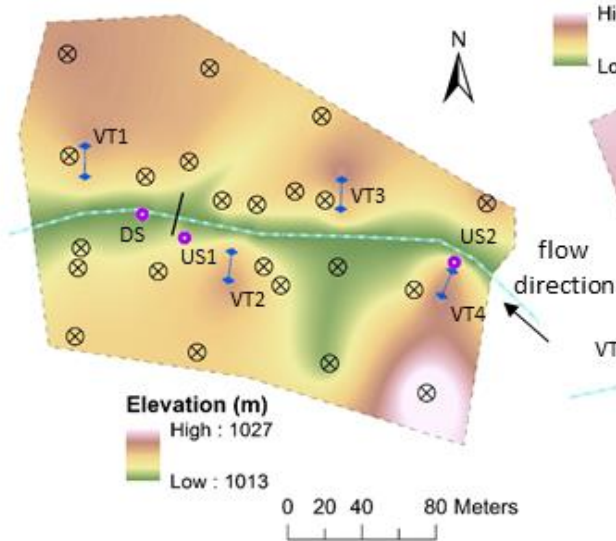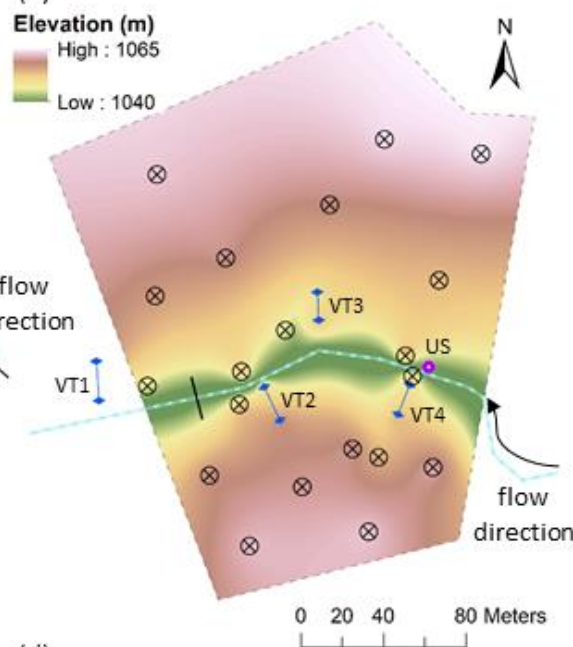
Figure 1: (a) Study Area. The bimodal rainfall region is north of the red line; the unimodal rainfall region is south of the red line (Luhunga and Djolov, 2017); (b) Kimokouwa study area; (c) Soweto study area; (d) Chididimo study area. Elevations are interpolated from GPS points taken during study. The elevation map includes only the area controlled by the community water groups.
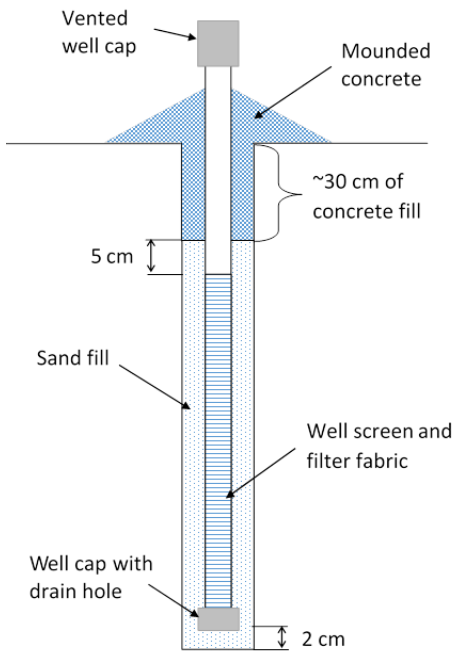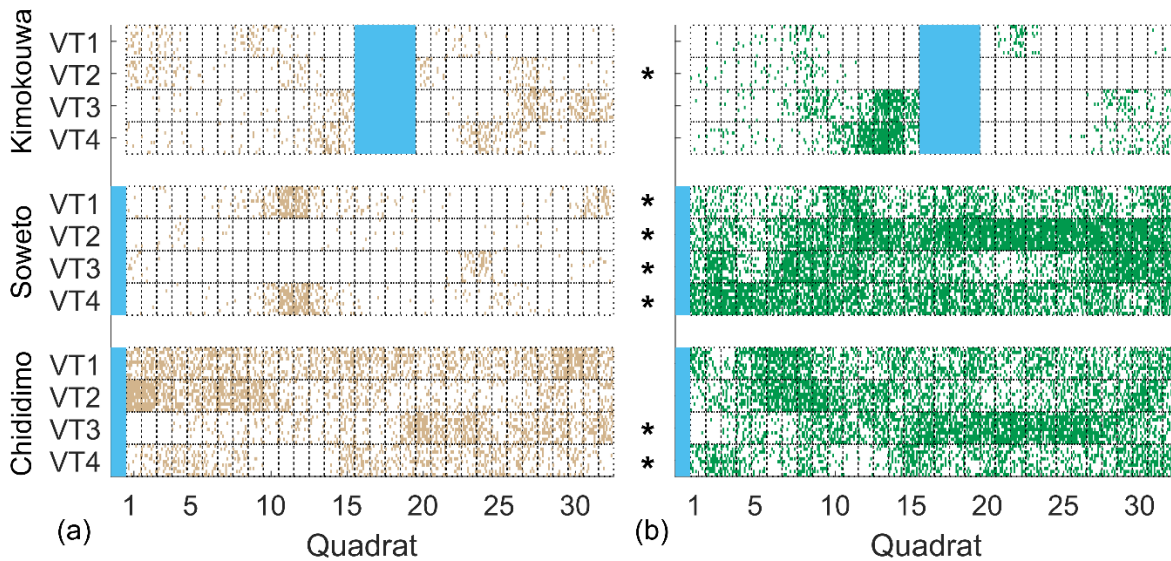
Figure 2: Schematic of the water table monitoring wells installed (adapted from Sprecher, 2008).

5 **Figure 3: Representation of percent vegetative cover for each transect at each sand dam during the (a) dry season and (b) rainy season. The stars indicate a significant difference (p<0.05) between the wet and dry season vegetative cover for that transect. The solid colour indicates the location of the stream relative to the transect. VT1 is downstream of the dam; VT2–4 are upstream.**
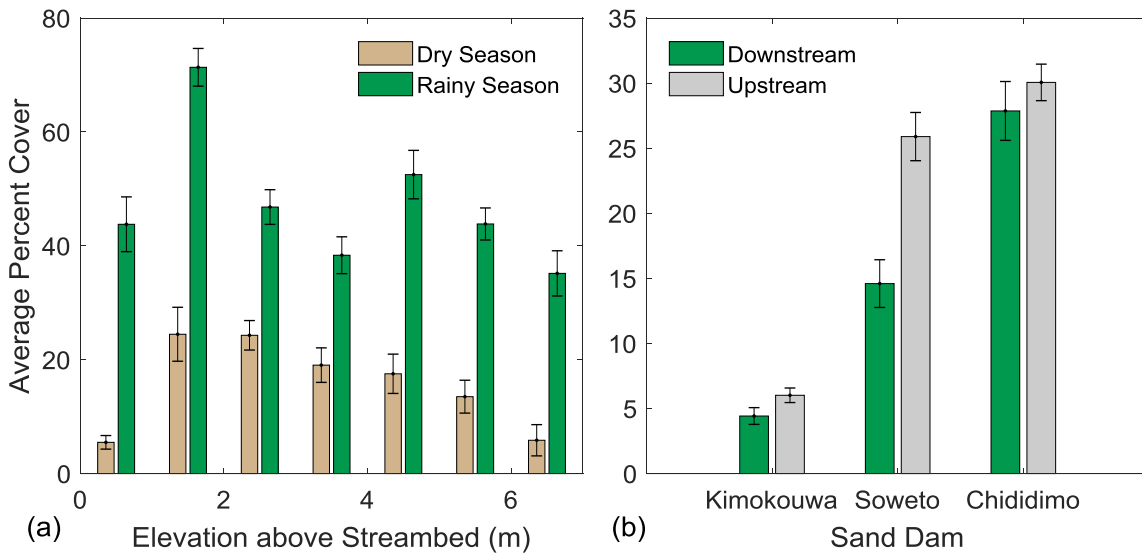
Figure 4: (a) Average percent cover at different elevations above the streambed for the dry and rainy seasons at the Soweto and Chididimo dams. Kimokouwa sand dam was excluded, because the sand dam is not functioning. Standard error bars are shown; (b) Average upstream and downstream vegetative cover at the three sand dams. Standard error bars are shown.
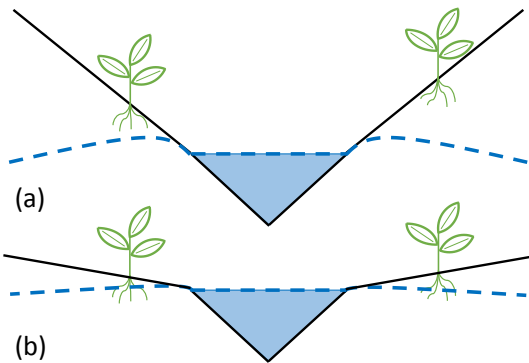
Figure 5: The roots of plants growing on a (a) steep slope will be farther from the locally raised water table created by a sand dam, and therefore have less access to soil water, than vegetation growing on a (b) gentle slope.
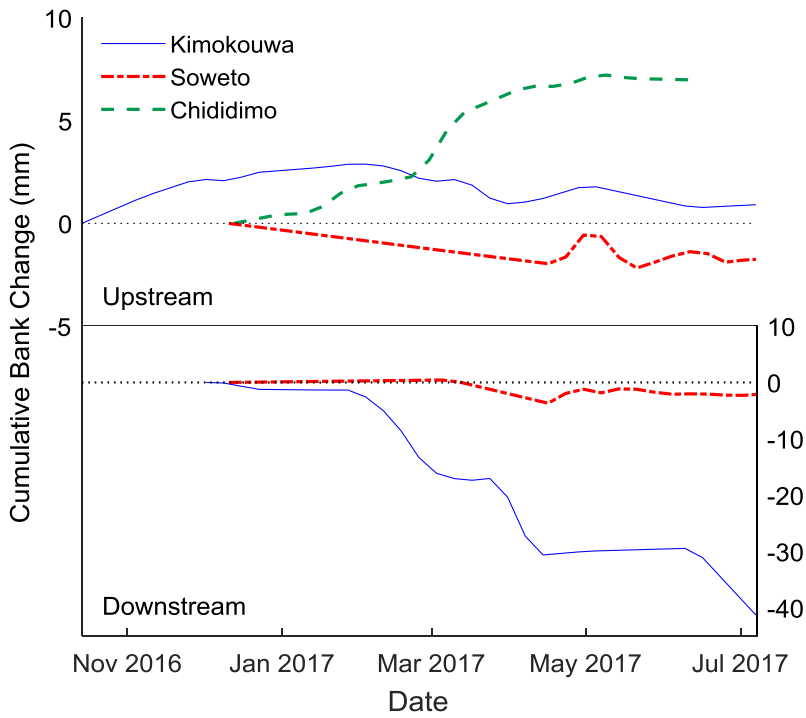
Figure 6: Cumulative bank change over the duration of measurement at each sand dam for the upstream and downstream pinned banks. A positive value signifies deposition, a negative value indicates erosion.
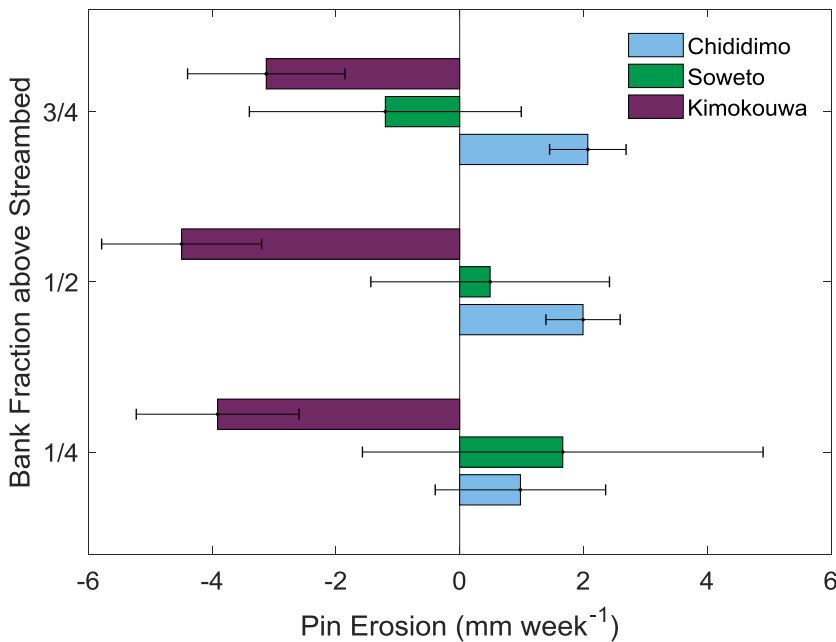
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Figure 7: Average weekly change in the bank soil at ¼, ½, and ¾ bank height. Positive values represent deposition; negative values represent erosion. Standard error bars are shown.

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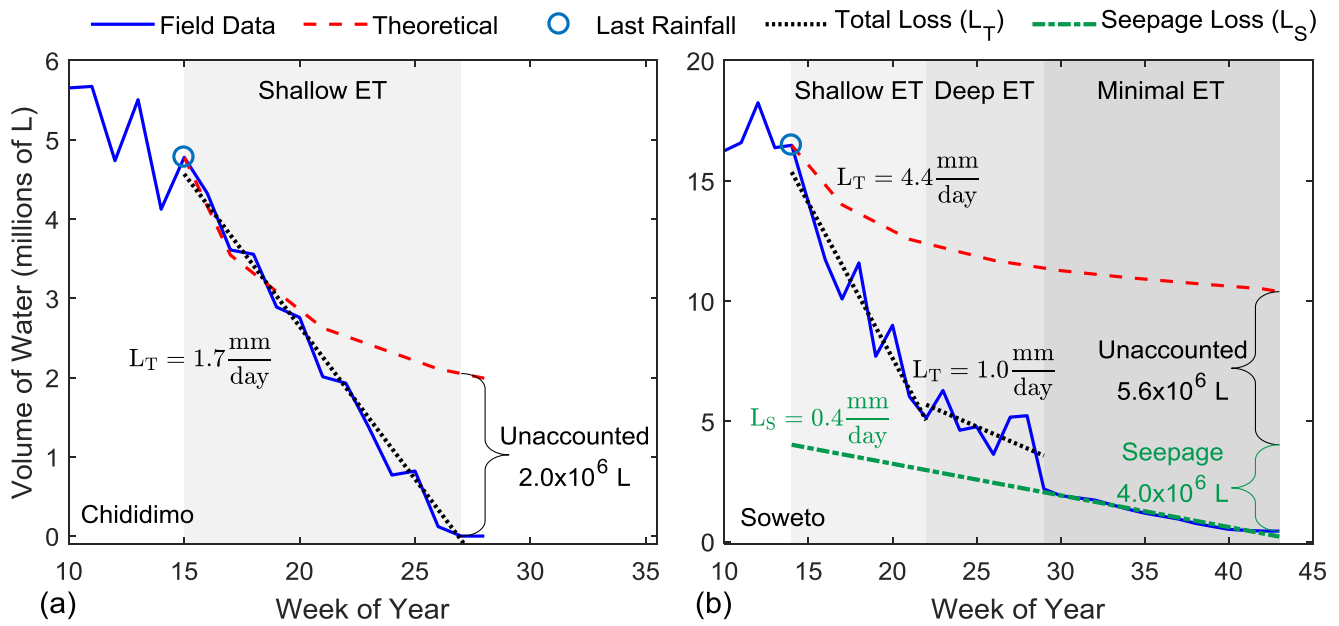
Figure 8: Volume of water in the area enclosed by the WTMWs of the (a) Chididimo and (b) Soweto sand dams. The field data line shows the volume of water in the study area during the specified week. The theoretical line, initiated at the end of the rainy season, shows the cumulative theoretical amount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

Table 1: Physical parameters of the three sand dams

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

Table 2: Site characteristics of each erosion pin section

Sand Dam	Site Name	Bank	Length of bank pinned (m)	Bank height (m)	Bank morphology	Floodplain vegetation	Bank material	No. of pins	Pin spacing (m) V	Pin spacing (m) H	Date installed
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.

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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