SUSTAINABILITY THROUGH AGRICULTURE AND MICRO-ENTERPRISES

SAND DAMS IN ZAMBIA

A NATIONAL GIS ANALYSIS OF TECHNICAL FEASIBILITY

May 8th, 2019

Photo: Polly Braden

NOTE: *This study is strongly based off Simon Maddrell's practical and technical sand dam manual (2018). Unless cited otherwise, descriptions of sand dams, their benefits, and their technical requirements were taken directly from the manual and should be accredited accordingly. The original document should be reviewed to ensure its contents were not misinterpreted. The author would like to thank Maddrell, Excellent Development, and Africa Sand Dam Foundation (ASDF) for empowering other water developers with their knowledge and experiences.*

INTRODUCTION

Sand dams are cement weir dams strategically sited on seasonal rivers in drylands so their reservoirs fill with sand (Fig. 1). Rain-season run-off is stored in the captured sediment, creating an artificial aquifer that, if sited properly, can provide water for drinking, domestic-use, livestock, and irrigation throughout the dry-season while recharging the local water table and greening the surrounding landscape. Sand dams are also advantageous as a rural water supply technology because they require minimal maintenance, the sand filters the water while protecting it from evaporation, and they can be installed in areas where poorly-weathered bedrock impedes the installation of boreholes. A more detailed description of sand dams and their benefits can be viewed at https://www.excellentdevelopment.com/.

Figure 1: A sand dam in Tanzania (source: Lauren Hall)

Despite the large-scale success of sand dams in neighbouring countries, there are only a few isolated examples in Zambia, and the feasibility of implementing scaled installation programs remains largely unknown. At first glance, Zambia has a lot to gain from sand dams; 77% of the rural population is impoverished by national standards (CSO, 2018) and 54% lacks access to improved water services (CSO, 2014). Lowering these statistics will become more and more difficult due to a rapidly growing population and climate change's impacts on water and food security. It is therefore critical that Zambia's poverty alleviation strategies inspect all possible approaches to improve their effectiveness and build resiliency against climate change. Sand dams may provide technological opportunity in this regard.

Intensive feasibility studies are required prior to the installation of sand dams in Zambian rural water development strategy because they require very specific conditions to be installed effectively. The purpose of this document is to initiate this feasibility study process and catalyze discussion amongst stakeholders. It uses GIS data sets of relevant environmental conditions to inspect the regional technical feasibility of installing effective sand dams across the country. The study is limited only to large-scale technical factors that determine where a sand dam could be built and does not inspect the numerous other considerations that determine whether and how a dam should be built. Any organization, community, or individual striving to construct a dam should seek expert advice before taking action.

METHODS – MAPPING TECHNICAL ASPECTS OF FEASIBILITY

Maddrell (2018) summarizes that for a sand dam to function effectively, three technical pre-conditions must be met:

1) **The sand dam must be sited on a sufficiently seasonal river**
2) **The river must have a sufficiently sandy sediment**
3) **There must be accessible bedrock.**

A seasonal river is required to ensure that the reservoir backfills quickly with desirable sediment; coarse, sandy sediment is required to ensure that the dam holds an adequate amount of abstractable water; and shallow bedrock is required to ensure that the dam is constructed on an impermeable layer in an economically and logistically feasible manner. Failing to meet these conditions will result in a dam with poor water storage because it either fills with layers of clay and silt or it fails to hold water due to seepage.

A specific set of climatic, fluvial, and geological factors determine whether the three pre-conditions are met (Table 1). Based on recommendations by Maddrell, these factors were categorized based on their desirability for sand dam construction. Using publicly available GIS data sets and ArcMap software, these ranked factors were then mapped and overlaid to inspect cumulative feasibility.

Table 1: Summary of technical factors and feasibility classifications. Lithological descriptions are only relevant to Zambia's geology. For general geological recommendations, see Maddrell (2018).

Factor	Relevant Pre-conditions	Enabling Conditions	Tolerable Conditions	Impeding Conditions
Rainfall (mm/yr)	1, 2	600 – 1000	1000 – 1200, 600 – 500	<500, >1200
Aridity	1, 2	Arid, semi-arid	Dry sub-humid	Humid
Seasonality index	1, 2	>1.2	1.2 – 0.6	<0.6
Lithology (based on Zambia's geology)	2, 3	Basement Complex (granitic), alkaline intrusive	Meta-sedimentary, silicic	Basalt, mudstone, Cenezoic sediments, alluvium
Soil depth (m)	3	0 - 4	4 - 6	>6
Soil type	2	Sand, loamy sand, sandy loam	Sandy clay loam, loam, clay loam, sandy clay (<40% clay), clay loam	Clay, silty clay, silty clay loam, silt loam, silt
Stream Flow	1	Ephemeral		Seasonal, Perennial
Stream Gradient (%)	1, 2	0.2 – 5	>5	<0.2

Some of the factors listed in Table 2 deserve clarification. An aridity index (AI) is defined as an area's average annual rainfall divided by its potential evapotranspiration, and areas are categorized as humid (AI > 0.65), dry-sub-humid (0.65 > AI > 0.5), semi-arid (0.5 > AI > 0..2), arid (0.2 > AI > 0.05), and hyper-arid (0.05 < AI) (UNEP, 1992). "Drylands" are considered any area with an AI less than 0.65.

The seasonality index (SI) measures the temporal heterogeneity of an area's rainfall pattern. Eqn 1 shows how it is quantified by dividing the sum of the absolute deviations from the monthly mean by the annual mean rainfall (Walsh and Lawler, 1981). Near-zero values have rainfall spread throughout the year, while high values (>1) indicate rainfall concentrated over a span of 1-2 months.

Eqn. 1) $$SI = [Abs(Jan_{avg} - Monthly_{avg}) + [\ldots] + Abs(Dec_{avg} - Monthly_{avg})]/Annual_{avg}$$

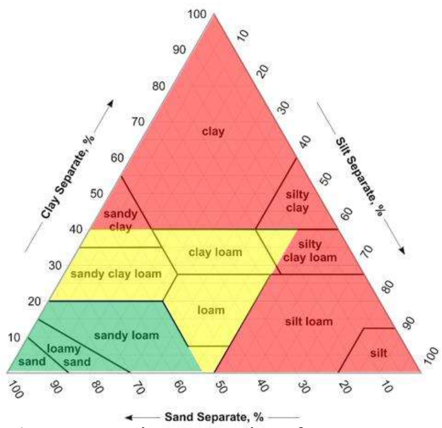

Figure 2: Soil texture classification diagram with modified regions of sand dam feasibility

The classifications of soil texture are based off a modified tertiary texture diagram (Fig. 2). The specific borders between the different categories are based off of Maddrell's recommendations, but were modified slightly for mapping algorithm simplicity.

Lastly, ephemeral streams are those which flow only after rainfall, seasonal streams flow throughout the rain season(s), and perennial streams flow year-round.

Table 2 lists the data sets used to calculate and generate Zambia's relevant conditions. All data sets are 30-arc sec resolution, publicly accessible, and, aside from the Africa-scale lithology maps, global in their extent. The author's names are linked to the hosting web page. All data involving precipitation are mean values averaged between 1970 and 2000.

Table 2: Data sources and treatments used to create feasibility layers

Factor	Open Data Source(s)	Data Treatments
Annual Rainfall	Fick and Hijmans, 2017	Calculated using averaged monthly rainfall data set
Aridity	Trabucco and Zomer, 2019	Mapped directly from data
Seasonality index	Fick and Hijmans, 2017	Calculated using Eqn. 1 and inputting monthly rainfall data set
Lithology	RCMRD, 2018; Persits et al., 2002; Baumle et al., 2007	Formed by combining the Africa-scale geological syntheses of RCMRD (2018) and Persits et al. (2002) and referencing them against provincial scale descriptions and observations (Baumle et al.,2007).
Depth to bedrock	Pelletier et al., 2016	Inferred from model of unconsolidated material above bedrock, defined as material that can be manually augered or excavated
Soil type	ISRIC, 2019	Calculated using summed models of clay, silt, and sand percentages and tertiary diagram classifications of particle size feasibility modified for mapping purposes (Fig. 2)
Stream Flow	Ferranti and Hormann, 2014	Watershed generated using topographic data and referenced against personal observations to isolate catchments corresponding to ephemeral streams (42 – 764km^2)
Stream Gradient (%)	Ferranti and Hormann, 2014; Dilt, 2015	Modelled using Dilt's stream gradient tool box and inputting generated ephemeral streams

To systematically combine the layers of feasibility, each of their cells were assigned values based on the desirability of their conditions: 1 for enabling, 0 for tolerable, and -1 for impeding. The distribution of scores were overlaid and summed to yield a cumulative "feasibility score" with a possible range of 6 to -6 (stream-gradient, the seventh factor, was excluded at this stage because its data does not cover the full extent of the country). Low-scoring values thus represent areas where multiple impeding conditions make them very unsuitable for sand dam construction; near zero values represent areas with only tolerable conditions or where enabling conditions are undermined by impeding ones; high scoring values represent areas where multiple enabling conditions coexist in the absence of impeding ones, defining the target regions for sand dam programs.

This map was further modified to reveal areas where the presence of certain "game-ending" conditions prevents the feasible construction of sand dams, regardless of the favourability of its other conditions (Fig. 6b). Interpreting Maddrell's manual, it was decided that areas with inaccessible bedrock (soil >6m thick), shallow stream gradients (<0.2%), or excessive rainfall (>1200mm) are rendered unfeasible, in addition to areas falling within national protected areas.

RESULTS: DISTRIBUTION OF TECHNICAL FEASIBILITY

The distribution of climatic factors of sand dam construction in Zambia are shown in figure 3. Due to their reliance on precipitation data, the maps strongly resemble each other, all displaying a large latitudinal gradient. Annual precipitation and aridity both show favorable conditions over the majority of the country. Although the desired seasonality index value of 1.2 is never reached, figure 3e shows how large areas host SI values >1, meaning that most precipitation in these areas falls within 3-months or less (Walsh and Lawler, 1981).

Figure 4 shows the geological factors of sand dam construction in Zambia. The Cenezoic sediments that occupy Western Province are unconsolidated and therefore are unfavorable both in terms of lithology and depth to bedrock. Figure 4c reveals the dichotomy of Zambia's soil depths, with deep profiles above sediments and alluvium and shallow profiles elsewhere. Overall, the areas of unfavorable geologies outweigh those favorable, but technical feasibility is still maintained over substantial regions, especially if potentially feasible (meta-sedimentary) geologies are inspected further and found to be suitable. The coverage of favorable geology is dominated by undifferentiated basement, which hosts the ideal granitic rock, some of it metamorphosed.

Figure 5 shows seasonal rivers with various stream gradients. The influence of lithology on topography is evident by the concentration of gently sloped streams above Cenezoic sediments, alluvium, and basalt. The remainder of the country is characterized by streams with favorable slopes.

Fig. 6b reveals how Zambia's feasible area for sand dam construction is constrained in the West by geologic factors and in the East by climatic factors. Overall, four provinces maintain a substantial coverage of desirable conditions: Southern, Lusaka, Central, and Eastern. Each of these provinces host an internal, central hotspot of feasibility, the largest being the Choma-Kalomo block in the Southern Province, a geological unit composed of granite and gneiss (Baumle, 2007). A feasibility score of 6 is never reached anywhere in the country due to the fact that only tolerable seasonality index values exist throughout the country. All of the remaining provinces, including the NW of Southern Province (Kafue Flats) host conditions unfavorable for sand dam construction.

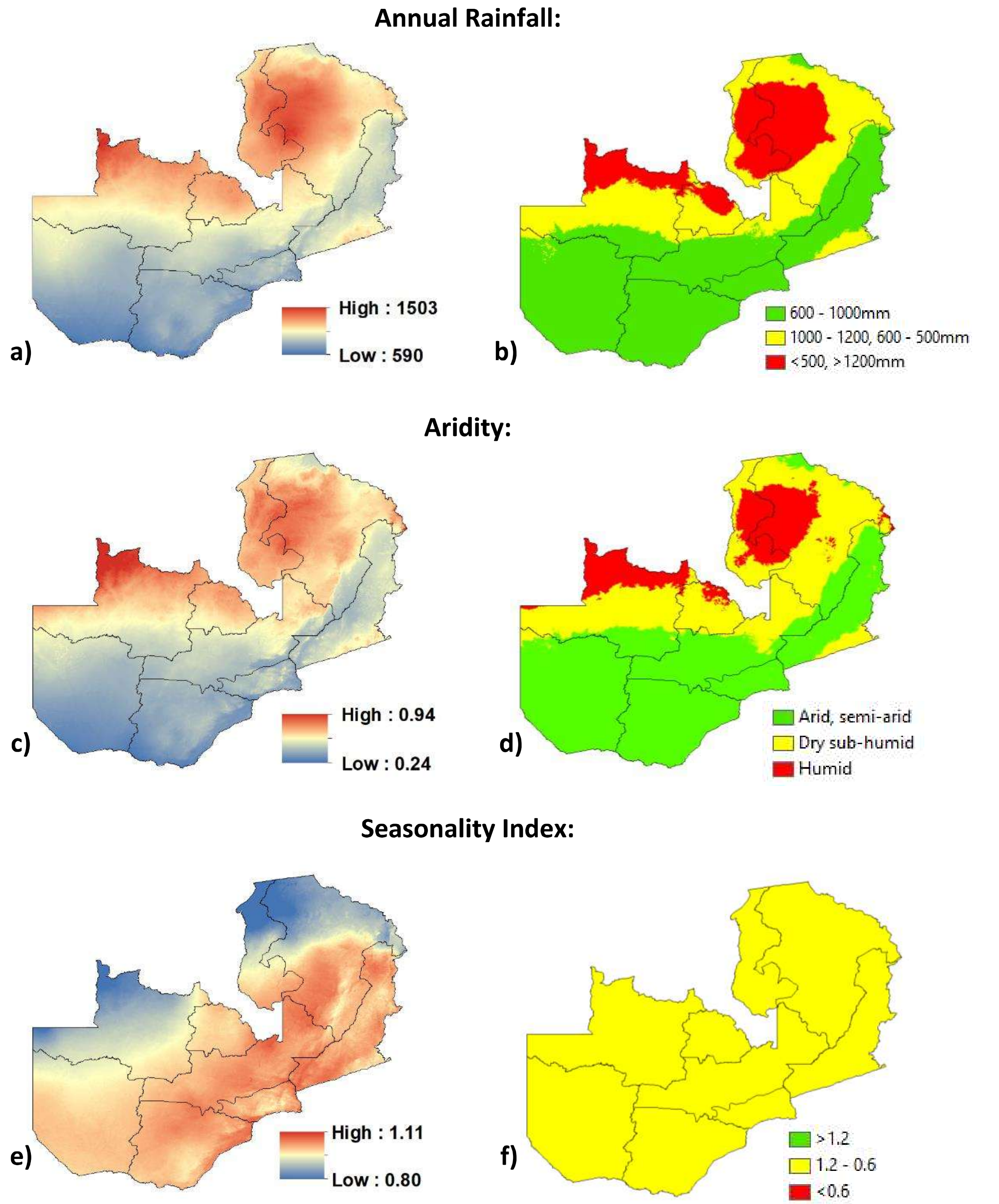

Figure 3 – Climatic factors of Zambian sand dam construction: a) Distribution of mean annual rainfall in Zambia, averaged throughout 1970 – 2000 (Fick & Hijmans, 2017); **b)** Distribution of sand dam construction feasibility based on mean annual rainfall recommendations made by Maddrell (2018); **c)** Distribution of aridity index values in Zambia (Zomer et al., 2008); **d)** Distribution of sand dam construction feasibility based on aridity recommendations made by Maddrell (2018); **e)** Distribution of seasonality index values in Zambia, calculated from Fick and Hijman's monthly rainfall data (2017); **f)** Distribution of sand dam construction feasibility based on seasonality recommendations made by Maddrell (2018)

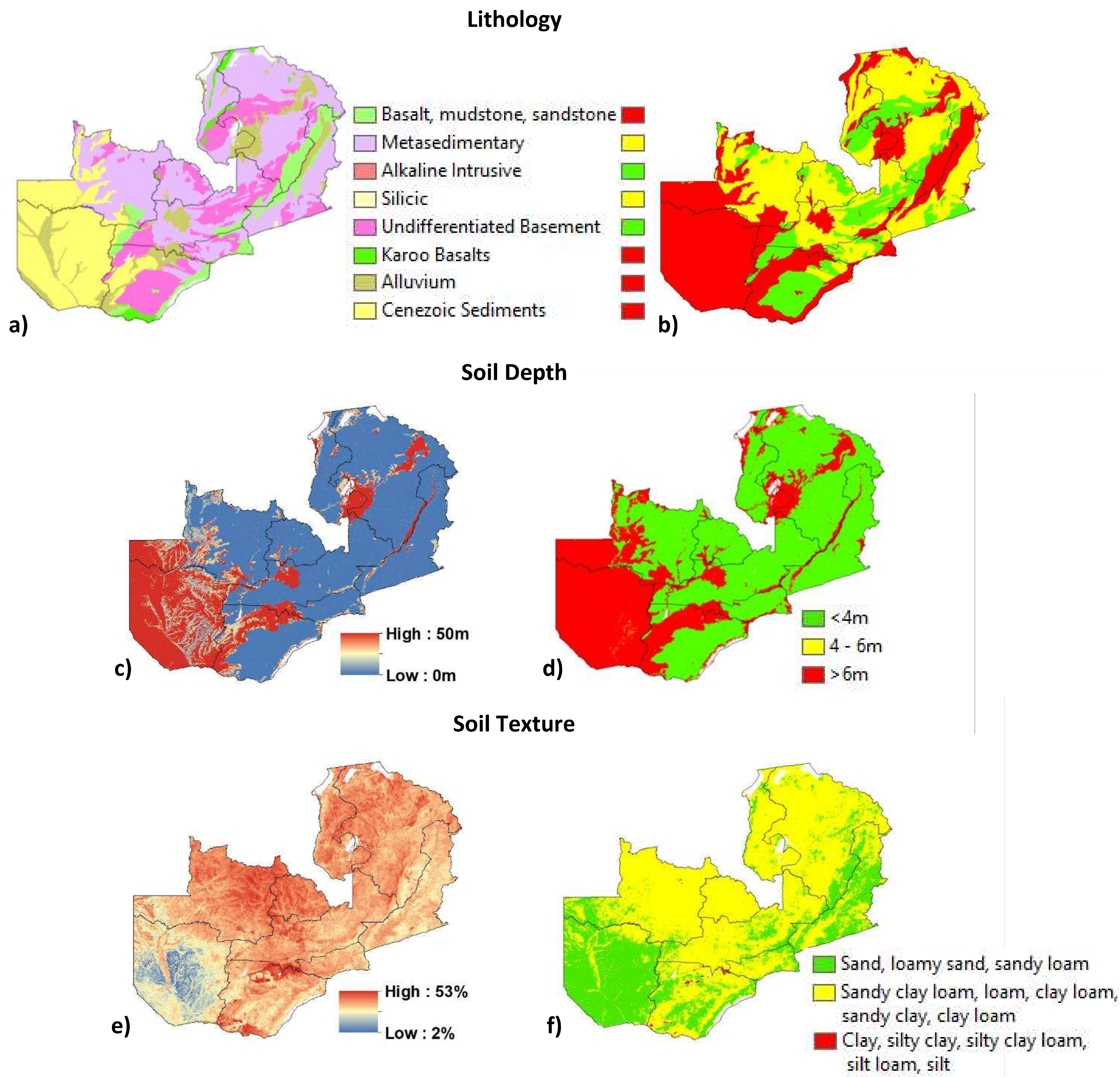

Figure 4 - Geological factors in sand dam construction: a) A modified map of Zambia's lithology (RCMRD, 2018; Persits et al., 2002; Baumle et al., 2007); **b)** Distribution of sand dam construction feasibility based on geology recommendations inferred from Maddrell (2018); **c)** Distribution of unconsolidated material thickness in Zambia (Pelletier et al., 2016); **d)** Distribution of sand dam construction feasibility based on Maddrell's recommended depths to bedrock (2018); **e)** Surficial clay content in Zambia (ISRIC, 2019); **f)** Distribution of soil textural classes categorized by feasibility for sand dam construction

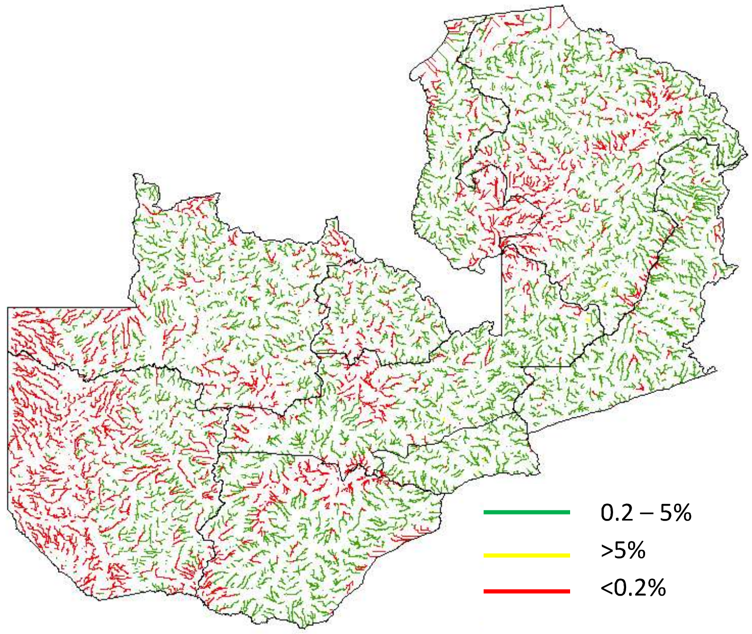

Figure 5: Streams with catchments 40 – 765 km^2 in Zambia suitable for sand dam construction based on stream gradient

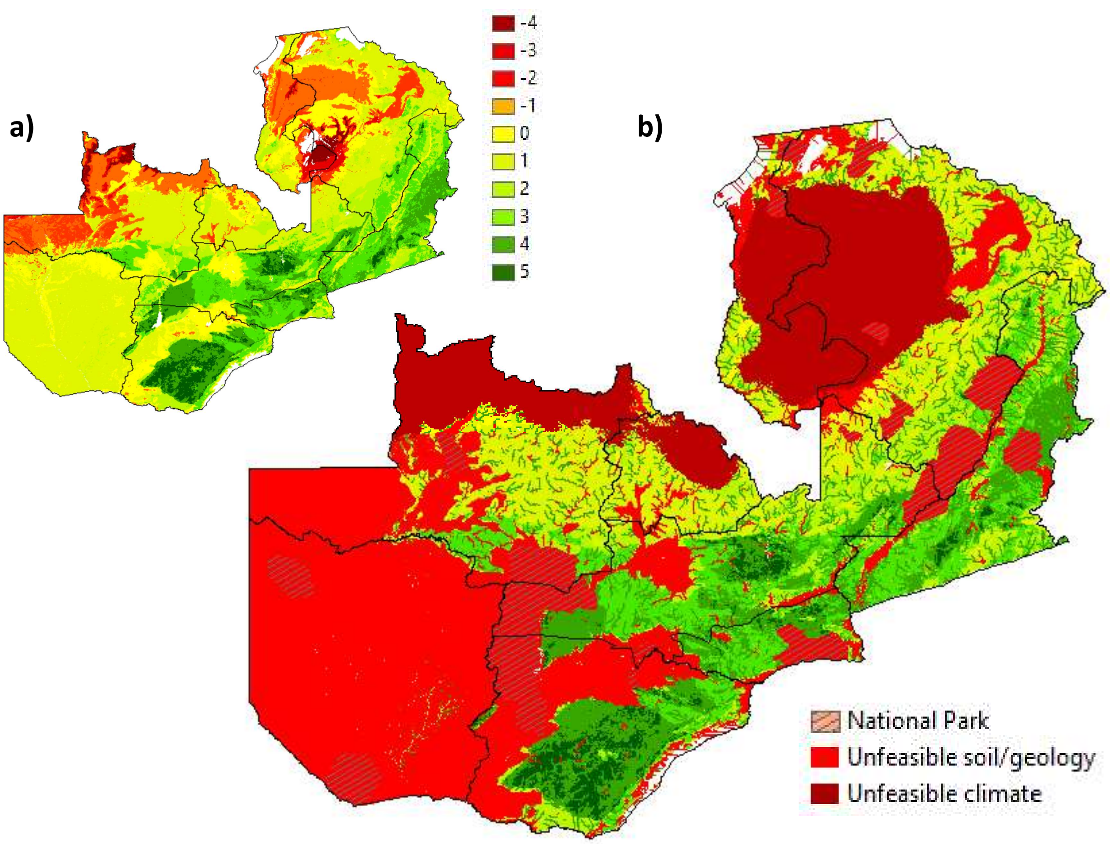

Figure 6: a) Distribution of cumulative technical feasibility scores of sand dam construction in Zambia based on annual rainfall, aridity, seasonality, lithology, soil depth, and soil texture; **b)** Fig. 11a overlaid with conditions that render construction unfeasible.

DISCUSSION AND RECOMMENDATIONS:

There are multiple potential sources for error in the study. As a proxy for depth to bedrock, soil depth overestimates the feasible area because partially weathered bedrock (regolith) is not taken into account. At the same time, it could potentially underestimate depth to bedrock within the stream, as the erosive capacity of stream beds to cut through soil profiles to bedrock. Therefore, it is important to take conclusions based on soil depth with a grain of salt and verify them in the field. Also, the observations used to calibrate the catchment size are biased to the author's observations in the Southern Province. Due to the qualitative and southern-centric nature of this approach, it is possible that some of the mapped streams do not represent 2nd - 3rd order ephemeral flows, especially in climate, geology, and land-use regimes that differ largely from Southern Province. Still, the map provides a useful visualization of suitable topographies and can be adjusted with further investigation.

Overall, the GIS analysis found that Lusaka, Southern, Central, and Eastern Province all host extensive areas where conditions are likely suitable for sand dam construction. Based on technical factors alone, scaled sand dam programs in each of these provinces are likely feasible. The same cannot be said for the remaining provinces, all of which host overlapping undesirable conditions. Although scaled programs are likely unfeasible, the author cannot refute the feasibility of small-scale sand dam programs in these provinces within pockets of tolerable conditions or areas misrepresented by estimations in the data sets. Inspection into the feasibility of meta-sedimentary geologies might expand feasible construction areas in these regions slightly.

For the four provinces with suitable conditions, the first recommended step in proceeding is to engage potential stakeholders. This report will be shared with both Zambian government offices and organizations who could potentially have a role in implementing a future program, including the National-Rural Water Supply and Sanitation Programme, The Department of Water Affairs, The Ministry of Agriculture, United Nations Development Program, Excellent Development, and the Africa Sand Dam Foundation. This step is important prior to further feasibility studies to help inform the decisions within those studies and help partners develop a familiarity with sand dams.

Although the details of the subsequent steps will depend on the outcomes of stakeholder discussions and logistical opportunities, there are certain steps that are recommended by Maddrell and the author. Further desktop GIS studies can be conducted using socio-economic data to determine priority regions. Distribution of poverty, access to clean water, vulnerability to climate change, and land-use change are all indicators that could inform regional choice. Stakeholders within the province can verify technical feasibility and provide finer-scale clarifications. Once a priority region is chosen, a pilot project can begin to be designed and proposed. The details of the pilot project are strongly dependent on the implementing partners, but thorough community engagement and sand dam skill capacity building for local partners are mandatory components.

Lastly, the fact that this study was conducted remotely solely on continental-scale, publicly accessible data means that the same process can easily be repeated for other countries with currently unknown sand dam feasibility. Notably, the fine-scale calculation of seasonality index, stream-gradient visualization, and feasibility score mapping are components that could be refined to bolster the feasibility study methods outlined in Maddrell's manual.

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