# Technical Feasibility Framework for Sand Dams Applied to Eastern Chad

By

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WEDC Developing knowledge and capacity in water and sanitation

Loughborough University

## Dedication

To Claire, Mary and Michael


## Acknowledgements

I would like to express my gratitude to my supervisor, Brian Skinner, and to the entire WEDC faculty. I thank International Aid Services in Chad for releasing me to undertake this research, and the team in Chad for their support. Finally, I am indebted to my wife who has stood by me throughout all this.


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## ABSTRACT

This paper focuses on the technical aspects of sand dams, establishing a feasibility framework comprised of three criteria with which to evaluate sand dam suitability. Sand dams are an effective and affordable type of rainwater harvesting technology for arid regions. However, they must only be undertaken in specific contexts where conditions are favourable. Adequate water supply must be ensured by considering the region’s rainfall and geology. Sufficient storage capacity will depend on the volume of sand behind the dam and the river’s sediment characteristics. Affordability will be determined by the availability of construction materials, the dimensioning of the dam, and users’ willingness to pay. This feasibility framework is applied to Hadjer Hadid in eastern Chad, where eleven prospective sand dam sites are analysed. 72% of the sites are considered favourable; on this basis, sand dams are considered a viable option for addressing water needs in eastern Chad.

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*(iii) All field work and computer programming has been carried out by me with no outside assistance*

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# EXECUTIVE SUMMARY

## AIM AND RESEARCH QUESTIONS

This research **aims to determine whether sand-dams are technically feasible in Eastern Chad**. This is accomplished by answering three research questions:

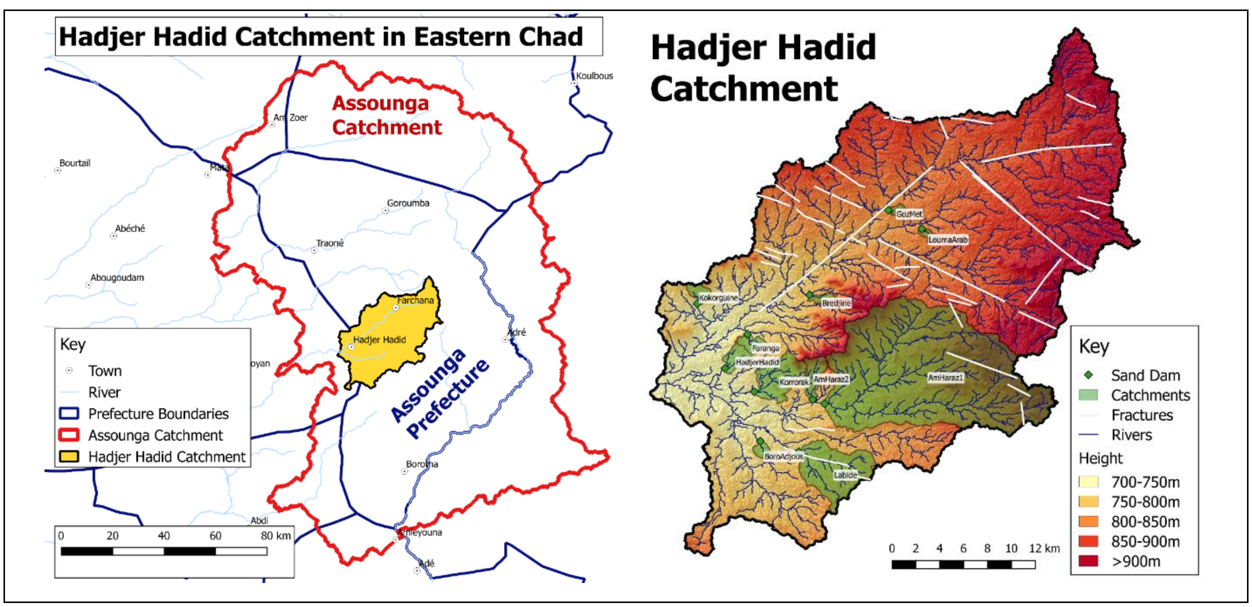
1) What technical criteria and conditions determine the feasibility of sand dams?
2) Which sites should be prioritised as being particularly appropriate for sand dams?
3) To what extent does Eastern Chad provide an appropriate context for sand dams?

## SCOPE AND DEFINITIONS

***Sand dams*** are cement structures constructed across sandy riverbeds in arid climates. The rivers only flow during rainy season, and this causes the build-up of a coarse sand reservoir behind the dam, which comprises 25-40% water (Excellent Development, 2015). During the dry season water is extracted using hand-pumps or gravity fed piping at the food of the dam. This research is limited to sand dams, and does not consider the other types of groundwater dam (Van Haveren, 2004:3).

***Technical feasibility*** is concerned with the physical processes related to sand dams, and limits its scope to explore these factors, including geology, climate, environment, and river characteristics. It does not attempt to address the socio-economic or political factors related to sand dam feasibility which are also critical, but beyond the purview of this research.

*Fig A: Assounga and Hadjer Hadid Catchments in Eastern Chad*




***Eastern Chad*** is defined using watersheds rather than political boundaries. It is the region contained within the Assounga catchment above (Figure A). The research focuses on a particular sub-catchment called Hadjer Hadid catchment. It is expected that results from this region will be typical of the wider Assounga catchment also.

### METHODOLOGY

Research question 1 is answered by developing a feasibility framework made up of criteria which determine the suitability of sand dams based on a range of technical parameters. The method used starts with a thorough literature review, from which key criteria are categorized and synthesized into a single coherent decision-making framework. Research question 2 is addressed by then applying this framework to eleven prospective sand dam sites in the Hadjer Hadid catchment. Satellite and climate data are acquired and integrated with field data collected during site visits to establish which sand dams are viable. This provides the basis with which to consider the extent to which eastern Chad is appropriate for sand dams.

### SETTING THE STAGE

The literature base is polarized between the practitioner approach, which draws from field experience and case studies to develop manuals for sand dam implementation, and the analytical approach, which uses GIS and hydrological principles to provide a theoretical basis for evaluating sand dams. The paper bridges this dichotomy by synthesizing the two into a single framework. The technical analysis seeks to explore underlying physical processes, and then apply these practically so as to be used in feasibility assessments. Similarly, the analysis employs a multi-layered approach evaluating sand dams with reference to regional-level, catchment-level and local-level factors. In all this, it is important to remain conscious that sand dams are not universally applicable (Al-Taiee, 2010:35), and the task is to determine the conditions for which sand dams are viable. Three key criteria provide the structure for the technical analysis, which are considered in turn:

1. **Water Supply**: "sufficient supply & retention of water to ensure sand dam reservoir capacity is fully utilized."
2. **Storage Capacity:** "maximal and suitable water storage capacity available in the sand dam reservoir."
3. **Affordability:** "the sand dam is affordable, both initially in construction & long-term in its sustainability."

## TECHNICAL FEASIBILITY FRAMEWORK

### 1. WATER SUPPLY

The sufficient water supply criteria can be condensed into two parameters: geology and rainfall. The geology of the bedrock must ensure minimal water loss through groundwater infiltration. Thus bedrock is classified by its permeability: some rock types are unsuitable (gravel, sand, silt, limestone), some are suitable (clay, mudstone, gneiss), and some require further analysis (sandstone, granite, trachyte) since they depend on the location of fractures. Rainfall must be sufficient to replenish the reservoir each rainy season, with a high (95%) confidence threshold. Additionally, water demand must not have significant negative environmental impact on the surroundings, measured by determining whether it is within the existing natural variation of the region (Smakhtin & Weragala, 2005:9). The total rainfall required to fill the dam should be less than the standard deviation of the mean of total annual rainfall.

### 2. Storage Capacity

The volume of water stored in the sand dam reservoir, and its adjoining banks, must be adequate to meet its purpose. First of all, this reservoir must form through the accumulation of coarse sand during rainy season. Coarse sands are necessary to ensure sufficient porosity to store high volume of water, and their build up behind the dam depends on appropriate flow velocities of the river. For sediment transport to take place a minimum velocity of $0.2ms^{-1}$ is required in the river flow. The presence of coarse sands (grain size >0.2mm) in the riverbed prior to sand dam construction is a strong indication that river characteristics are favourable. However, even if sand is not found, the site will likely be appropriate so long as the catchment area behind the dam has a high mean slope (>2%), which to ensures erosion of coarse sediments, and the riverbed itself has a slope of between 1% and 5%.

### 3. Affordability

Cost-effectiveness of sand dams, compared with other water resource options, must be undertaken on a case-by-case basis. However, there are some parameters which are necessary for any sand dam to be considered affordable. Firstly, key resources (cement, local labour, local materials) must be available for sand dam construction to be viable. Secondly, the dam dimensions must be favourable, with a maximum river width <25 metres; a maximum riverbed depth (to reach the bedrock) of <3 metres; and a natural narrowing at the proposed sand dam site, to ensure a good ratio between the sand storage reservoir volume and the size of the sand dam to be constructed. Finally, it is essential to establish the users' willingness to pay, which will be severely undermined if (i) their water needs are already met elsewhere, (ii) there is a more proximate source of water (even if from an unimproved source), and (iii) the sand dam is hard for users to access.

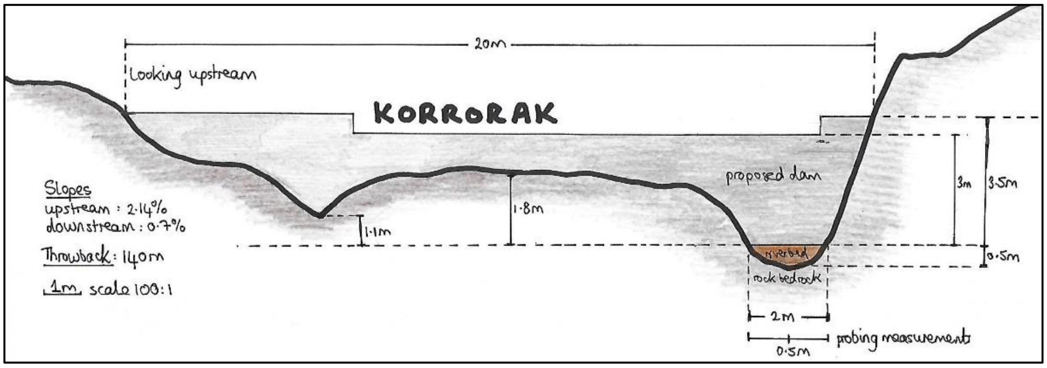
## Applied to Eastern Chad

This feasibility framework is then applied to the Hadjer Hadid catchment in eastern Chad, by analysing eleven prospective sand dam sites. Data was gathered using both GIS and field visits:

### Field Data

Sites were selected through a combination of GIS slope analysis and field visits. During these field visits measurements were taken for the dimensions of the proposed dam, sediment analysis was conducted to gauge porosity, probing rods were used to estimate the depth of the bedrock, and cross-section and aerial sketches were drawn up (see Figure A and Figure B below). Additionally, the presence of scoop holes and vegetation was recorded, as well as the distance to the nearest village.

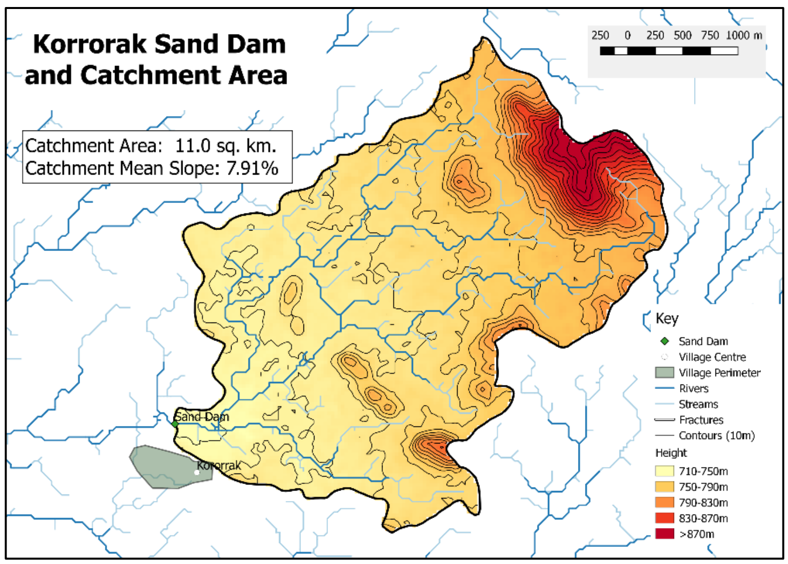
*Figure B: Example of cross-section sketch, from Korrorak site*




## GIS Data

GIS software was used to compile and process a broad range of data. Topographic data was acquired from the SRTM (Shuttle Radar Topography Mission). Geological and demographic data was provided by Réseau Tchad, an initiative focused on integrating hydrogeological data in Chad. Satellite imagery was used from Google Earth, and interpolated rainfall data was obtained from the Global Precipitation and Climatology Centre. This information was brought together and integrated on QGIS software and provide a tool for analysis and data presentation, as shown in Figure A and B.

*Figure C: Example of GIS catchment analysis*




## Feasibility Study

The data from the eleven sites was analysed and inputted into the feasibility framework.

**1. Water Supply**: the geology of the whole region is predominantly granite, which means sites which intersected fractures had to be excluded. In this way one site – Labidé – was discounted. Drawing on the water balance equation, the total evapotranspiration and precipitation in the catchment area for each sand dam was calculated and used to confirm that water supply was sufficient, with between 0.1% and 32.1% of river discharge being used to fill the sand reservoir. The environmental impact was analysed and one site – Louma Arab – was found to be outside the threshold of one standard deviation from the total annual mean rainfall, and was therefore discounted.

**2. Storage Capacity:** the volume of water stored behind each dam was estimated, having factored in water loss due to evaporation as well as the quantity of additional water stored in the river banks. By considering a ten month long dry season with a minimum per capita water requirement of 20 litres, the population supported by each sand dam was calculated, ranging from 96 people to 4632 people. The sediment data was processed and applied to estimate porosity at 33%, with sand deposits already present at every site. However, for completeness, the catchments' mean slope and the riverbeds' slopes were calculated and found to be within acceptable bounds for sand accumulation.

**3. Affordability**: the required materials are available locally – both cement and rock/sand/water. The local labour used to construct dams must be provided by users themselves. In one case – Faranga – the total population supported by the sand dam was too few to mobilise the required workforce, and so this site was discounted. The conditions for good access were positive for all sites except Faranga. Finally, the dam dimensions were evaluated, with all sites favourable, though they were ranked in accordance to their cost-effectiveness, which provided a means of comparison between the different sites, which is helpful when prioritising for implementation.

## CONCLUSION

The results yielded 72% (8 out of 11) sites favourable for sand dam implementation, which is also representative of a broader suitability for sand dams across the whole region. However, a proper assessment of socio-economic feasibility with thorough engagement of stakeholders is required in order to have a full picture. The paper recommended that a pilot sand dam initiative should be started in the region on the basis of the results, as well as a fuller feasibility which engages with communities.

## REFERENCES: EXECUTIVE SUMMARY

AL-TAIEE, Thair M., 2010. Groundwater Dams, a Promise Option for Sustainable Development of Water Resources in Arid and Semi-Arid Regions. In: *Integrated Water Resources Management and Challenges for Sustainable Development*. *Proceedings of the Second International Conference, Agadir, 24–26 March 2010.* IHP-VII Series on Groundwater No. 4. Paris: UNESCO.

EXCELLENT DEVELOPMENT, 2015. *Pioneers of Sand Dams*. Excellent Development [online]. Available online at: http://www.excellentdevelopment.com/site-assets/files/resources/publications/pioneers-of-sand-dams.pdf [accessed 6th June 2016].

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## ACRONYMS

| | | |
|---|---|---|
| ASTER | - | Advanced Space borne Thermal Emission and Reflection Radiometer |
| DEM | - | Digital Elevation Modelling |
| FAO | - | Food and Agriculture Organisation |
| GIS | - | Geographic Information System |
| GPCC | - | Global Precipitation Climatology Centre |
| GPS | - | Global Positioning System |
| GRASS | - | Geographic Resources Analysis Support System |
| IAS | - | International Aid Services |
| IRC | - | International Reference Centre (for Community Water Supply) |
| IWRM | - | Integrated Water Resources Management |
| QGIS | - | Quantum Geographic Information System |
| NGO | - | Non-Governmental Organisation |
| SAGA | - | System for Automated Geoscientific Analyses |
| SASOL | - | Sahelian Solutions Foundation |
| SRTM | - | Shuttle Radar Topography Mission |
| TauDEM | - | Terrain Analysis Using Digital Elevation Models |
| WEDC | - | Water Engineering and Development Centre |

# 1. Introduction

## 1.1. Why? Aim and research questions

This research aims to **determine whether sand-dams are technically feasible in Eastern Chad**.

This will be undertaken by considering the following three research questions:

Research Question **1**
- **What technical criteria and conditions determine the feasibility of sand dams?**

Research Question **2**
- **Which sites should be prioritised as being particularly appropriate for sand dams?**

Research Question **3**
- **To what extent does Eastern Chad provide an appropriate context for sand dams?**

Chapters 3, 4 and 5 draw from the literature base to develop a feasibility framework, exploring the physical processes involved in sand dams to put forward some key technical conditions, thus addressing research question 1. Chapters 6 and 7 then apply this feasibility framework to the eastern Chad context, considering eleven prospective sand dam sites in the Hadjer Hadid catchment and evaluating their suitability, thus addressing research question 2. Chapter 8 provides a summary of the whole process, and proposed way forward, thus answering research question 3.

## 1.2. What? Sand dams

Here only a brief introduction to sand dams in provided since later on three chapters (3, 4 and 5) are devoted to describing sand dams, and its associated physical processes, in depth.

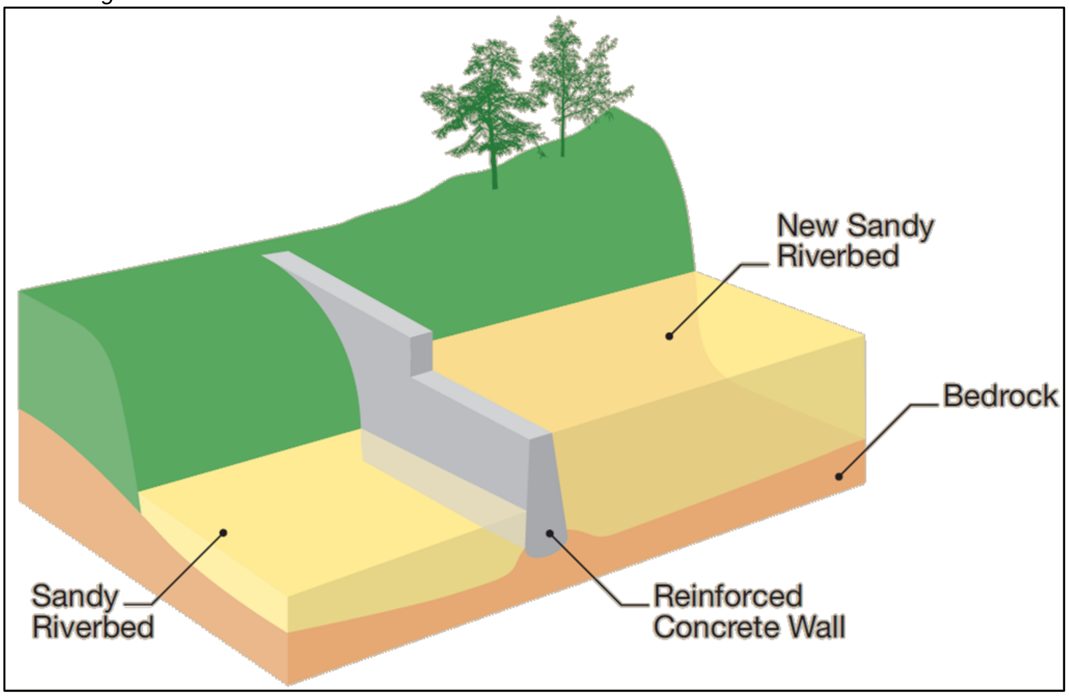
*Figure 1: Photo of sand dam in Kithyululu, Kenya*

*[Source: Excellent Development, 2015]*

Sand dams date back to Sardinia and Tunisia in the Roman times, and in more modern times to Arizona in the 18th Century (Barrow, 1999, Oweis et al., 2001). They have been widely implemented in parts of Africa and Asia (Nilsson, 1985), and are suited to arid climates, where rivers are ephemeral (do not flow year round). They should not be confused with sub-surface dams (see Section 2.3), which do not protrude above the ground.

Sand dams are cement structures which are constructed across sandy riverbeds. They have their foundations in the underlying bedrock, and are built to a height of 1-3 metres above the riverbed, as can be seen in Figure 2.

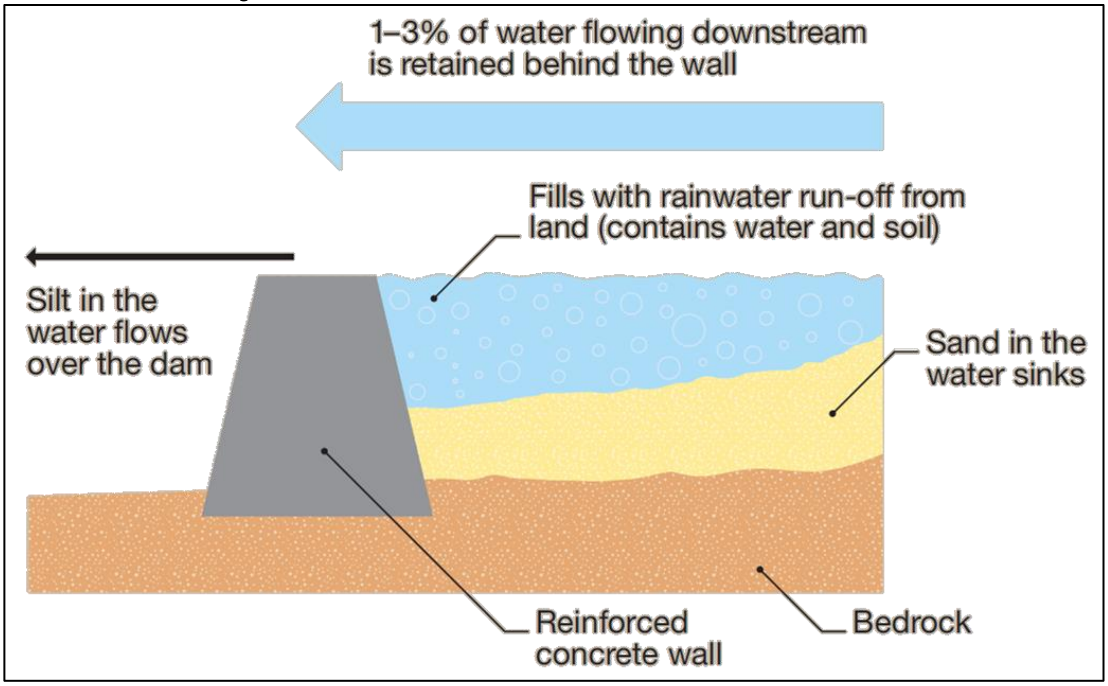
*Figure 2: Constructing a sand dam across a river*




*[Source: Excellent Development, 2015]*

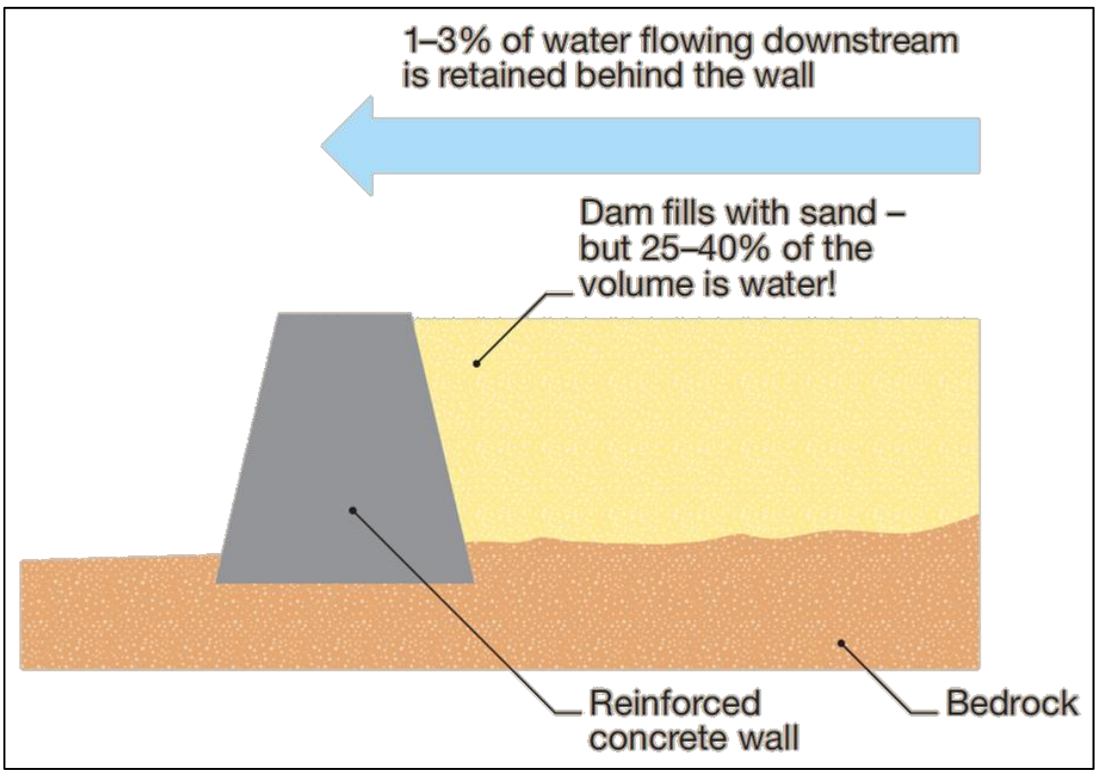
During the rainy season the river flows and transports sediment downstream. As the flow approaches the sand dam it slows, depositing the coarse sands whilst allowing silt and fine particles to carry on over the spillway of the dam. In this way sand accumulates behind the sand dam wall, as can be seen in Figure 3, until the dam is ‘full’ with sand. Each rainy season the river flows and the volume of sand behind the dam wall fills with water until it is saturated. Coarse sand typically stores 25-40% water (see Figure 4), which means that so long as the bedrock is impermeable, a significant quantity of water builds up behind the dam. In this respect the sand dam is merely a rainwater harvesting technology, making use of the valley’s geology and obstructing the river’s flow to create an under-ground reservoir. Water is then able to be extracted by users, either through shallow wells and handpumps on the river's edge, or alternatively by installing gravity fed piping in the riverbed allowing water to be extracted at the foot of the dam.

*Figure 3: Sand accumulating behind a sand dam*



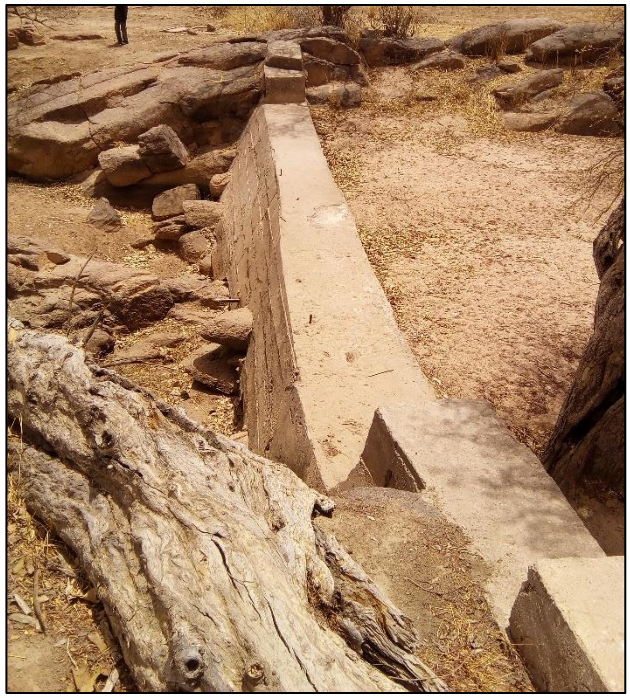

*[Source: Excellent Development, 2015]*

*Figure 4: Sand reservoir behind built behind a sand dam*



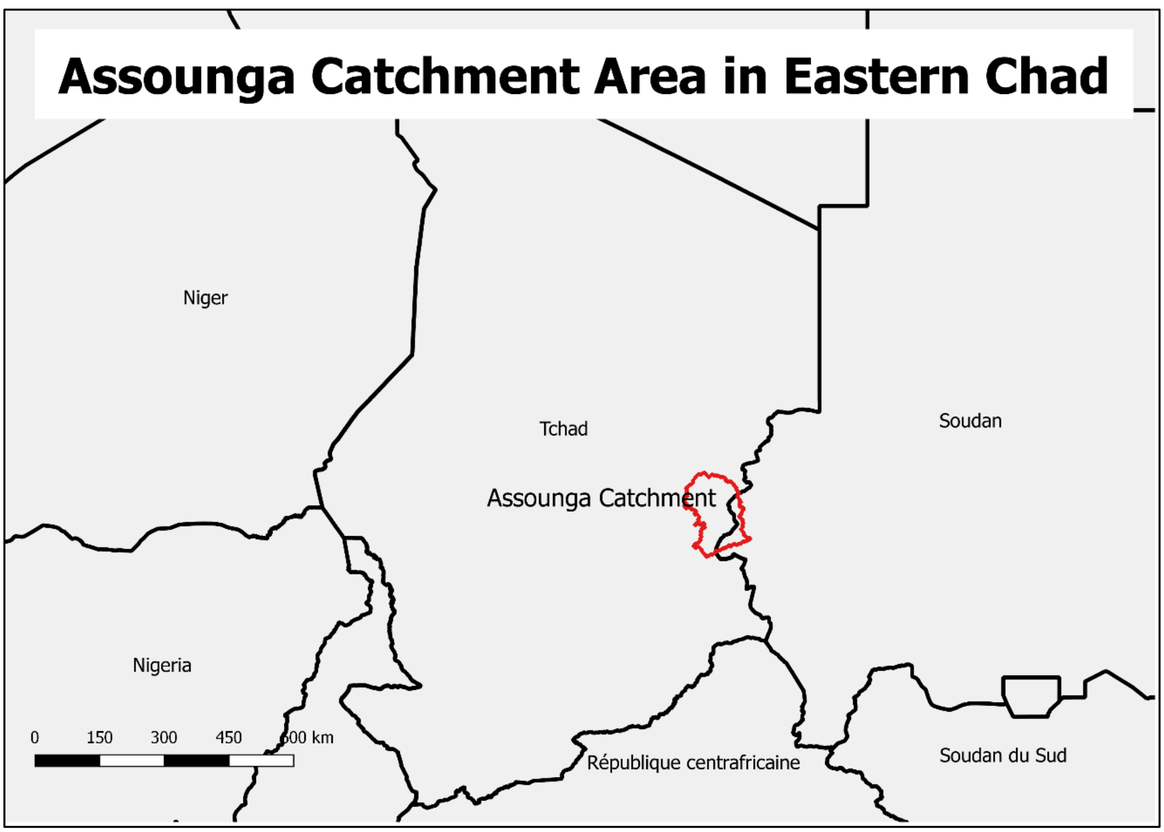

*[Source: Excellent Development, 2015]*

## 1.3. Where? Eastern Chad



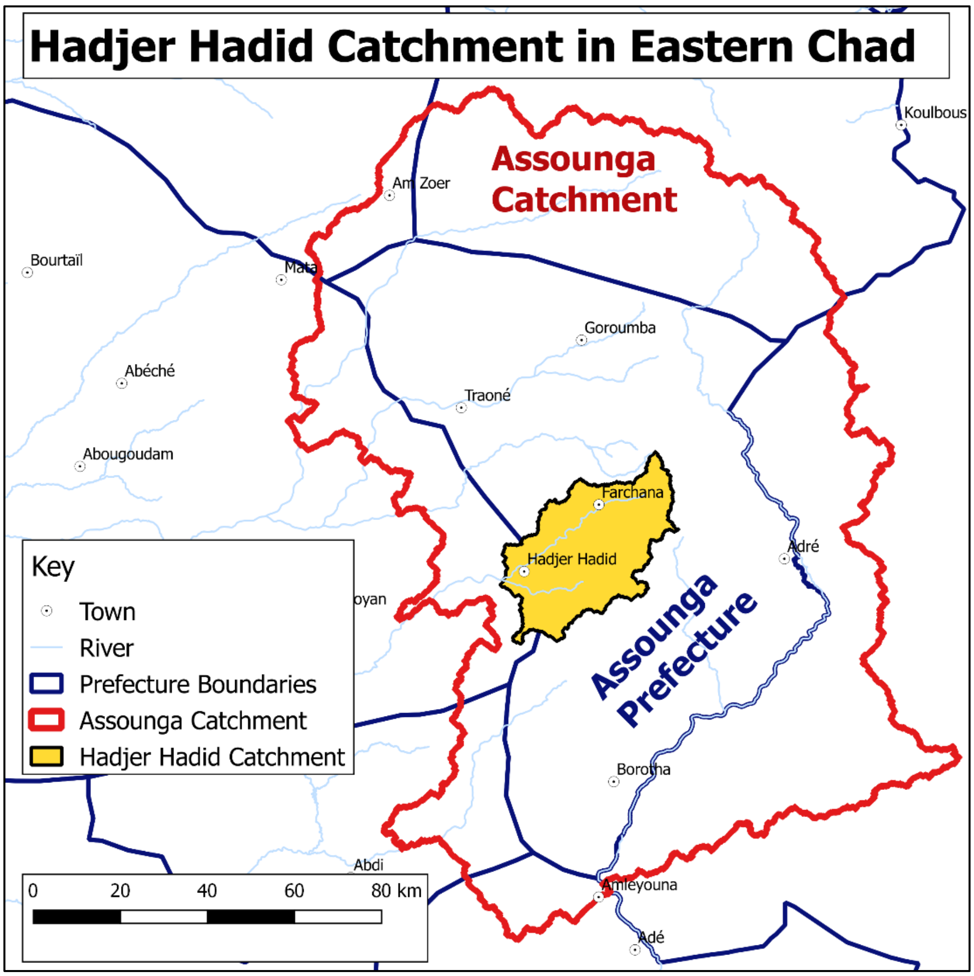
Chad is a developing country in the Sahel region of Africa (Figure 5). The country is both of personal and professional interest to the author, who has been based in the city of Abeche for four years, engaged in water resources management. The region of eastern Chad in general, and the Assounga region in particular, is of interest for sand dams. There are almost no examples of sand dams being constructed in Chad to date (see Section 6.1) but at first glance the climate and geology seems to be favourable for their implementation. Furthermore, sand dams have been constructed with success across the border in Sudan.

*Figure 5: Map of Chad and the Assounga catchment area*



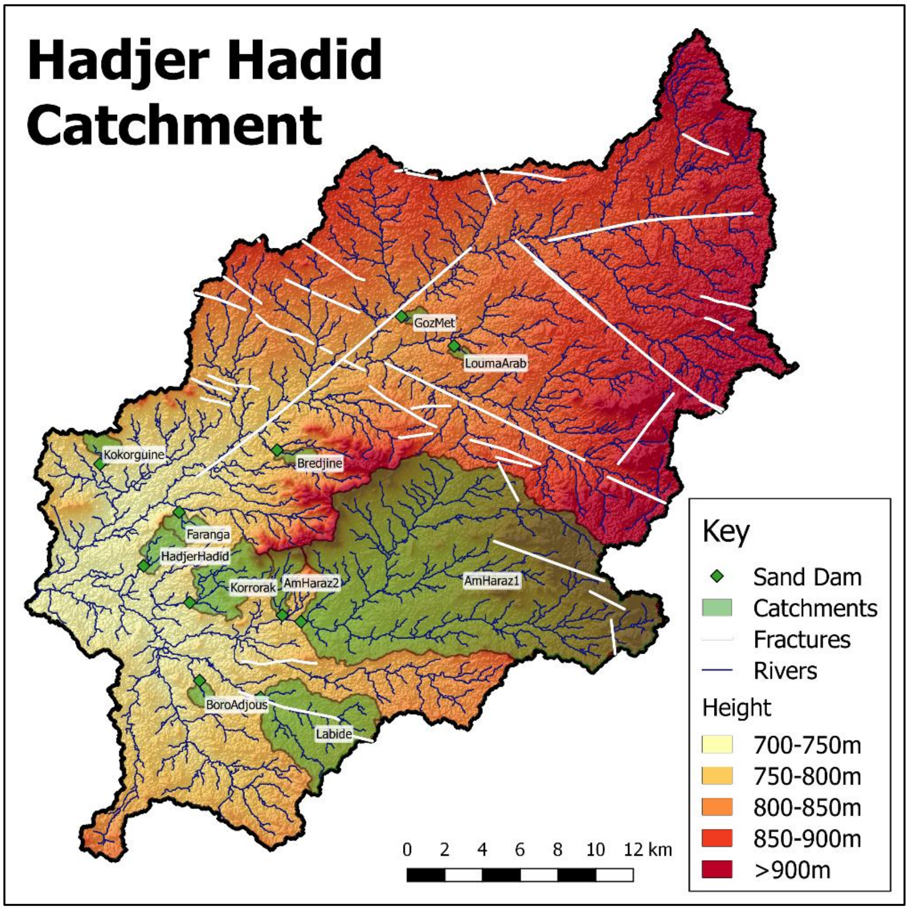
A desk based method was used to specify the geographic scope of the research. Consistent with an Integrated Water Resources Management (IWRM) approach, watershed boundaries have been prioritised over political boundaries to determine the scope (Reed et al., 2004). The organization International Aid Services (IAS), with whom the author works, has a field office in Hadjer Hadid, in the Assounga prefecture of Chad (Figure 6). Consequently it was selected for the field work component of the research.

*Figure 6: Assounga and Hadjer Hadid catchment*




GIS catchment analysis was used to identify a specific Hadjer Hadid catchment, bounded by watersheds, which is presented below in Figure 7. The field work and data collection (Chapter 6) has been limited to this region, though hydrological, geological and climate conditions are similar in other parts of Eastern Chad in general, and Assounga in particular. Thus we have established a geographical scope with which to undertake this research. Figure 7 presents the Hadjer Hadid catchment, and eleven proposed sites for sand dams are marked, which provide the data points with which sand dam feasibility for the region more generally will be evaluated.

*Figure 7: The Hadjer Hadid catchment area.*




## 1.4 How? Research method

The scope is restricted to sand dams only, and other types of groundwater dams are not the purview of this research (see Section 2.3). Additionally, only technical aspects of feasibility are considered here. Other factors (socio-economic, political, legal, etc.) must also be evaluated prior to determining the feasibility of any proposed sand dam project. However, here we focus exclusively on the technical aspects: those factors which relate to physical and environmental processes.

The methodology is comprised on three components to this research.

**1. Literature review methodology**: the method for selecting literature is described in Section 2.1.1. and provides the foundation for the desk based study into sand dam feasibility. The sources are divided between those focused explicitly on sand dams and those describing physical processes by which we are able to understand the way sand dam operate. In addition to this, a thorough evaluation of literature trends is provided in Section 2.4, and this provides a springboard from which the technical analysis is able to launch.

**2. Technical Analysis Methodology:** the technical analysis is a desk based undertaking which seeks to synthesise the existing knowledge base on sand dams into a feasibility framework. This is a form of extended literature review which goes beyond in two ways. Firstly, it links theory and practice in a new way, by undertaking thorough analysis of sand dam processes to establish a theoretical foundation upon which to hang empirical observations. Secondly, it provides a tool with which to guide decision making about sand dam feasibility, which can be applied by practitioners to assess sand dam feasibility. The literature base has been thoroughly reviewed with many criteria and conditions drawn out and synthesised by the author into a new paradigm for evaluating sand dams. This answers research question 1: *What technical criteria and conditions determine the feasibility of sand dams?*

**3. Feasibility Study Methodology:** this technical analysis is applied to the context of eastern Chad. The author visited the only three sand dams that have been constructed in Chad to date, and making use of lessons learned, combined with GIS analysis and field visits, eleven prospective sites were identified in the Hadjer Hadid catchment. This process methodology is described in Section 6.4. These sites are then investigated using a two-pronged methodology: firstly, a desk based study analyses topographic and climate data through GIS processes (described in Section 6.3 and 6.2); secondly, data for a range of variables is collected on field visits, as described in Section 6.5. This data is then analysed and inputted into the feasibility framework (Chapter 7) to answer research question 2: *Which sites should be prioritised as being particularly appropriate for sand dams?*

The knowledge gained throughout the course of the above components allows us to make recommendations about the feasibility of sand dams in Eastern Chad, which enables us to answer research question 3: *To what extent does Eastern Chad provide an appropriate context for sand dams?*

The research has a number of limitations which are discussed fully in Section 8.1. The desired impact of this research is that:

- The technical feasibility framework can be used by practitioners around the world to assess the suitability of proposed sand dam sites, ensuring a greater level of success in sand dam implementations
- The result of the feasibility study for eastern Chad provides a foundation for sand dam implementation in eastern Chad, so that many local communities can benefit from improved access to water.

# 2. SETTING THE STAGE

## 2.1. LITERATURE OVERVIEW

### 2.1.1. METHODOLOGY

Sand dams are described in a broad range of literature sources, both from practitioners and academics (see Section 2.4.1). In light of this paper's attempt to provide a feasibility framework for sand dams a comprehensive literature survey is essential. The literature should be as diverse as possible, both geographically and disciplinarily. To this end, a substantial and systemic literature selection process was undertaken in the following manner:

**1. Key word search of academic sources**: the Loughborough University 'Library Catalogue Plus' was used, which has access to global academic databases through its advance search utility. Searches were conducted with the following key words: "sand dam" / "sand storage dam" / "groundwater dam" in combination with "feasibility" / "case study" / "hydrology" / "technical". This returned a broad range of results, which were analyzed by a precursory reading of their respective abstracts. Two key criteria were used to select papers for further study. Firstly, confirmation was required that the source did indeed deal with sand dams, in line with this paper's definition and scope (laid out in 2.3). Secondly, a partial or whole focus on feasibility – i.e. speaking to the contributing factors which determine sand dam success.

2. **List of References in identified literature:** the body of literature that was found through the key word search above was then used as a means of identifying other key articles, by examining the list of references for each one. This was found to be a very effective way of adding to the list of key sources, making use of others' efforts to compile important sources. These additional articles were then searched for in academic databases, and scrutinised in the same way as outlined above.

3. **Online databases**: in reading the body of literature, a number of key organisations were identified, who either specialised in sand dams or had contributed significantly to academic dialogue regarding sand dams. Many of these have their own databases of resources, and these were used to look for further pertinent literature on sand dam feasibility. The following databases were used, with the same key search approach outlined above:

- *SamSam Water Library*: this organisation focuses exclusively on sand dams and has put together a resource library which can be searched and accessed from its website: http://www.samsamwater.com/library.php.
- *WEDC Knowledge base:* WEDC has significant resources online focused on water in the developing world, of which sand dams are one. In particular, their conference proceedings

and access to briefing notes, as well as a database of Masters' and PhD theses, was useful. Their website is: https://wedc-knowledge.lboro.ac.uk/search.html

- *IRC Wash Resources:* this is a water and sanitation think tank which has extensive papers and documents available online at their resource centre: https://www.ircwash.org/resources

These sources proved particularly profitable in accessing non-peer reviewed papers, such as Masters Theses or technical briefings, as well as a range of case studies and practitioner reports with concrete examples of sand dam surveying and implementation.

4. **Internet Searches**, using Google Scholar (https://scholar.google.co.uk/): the key word searches were repeated using more generic internet searches, and this provided a broader range of sources.

5. **Personal Correspondences:** the Rural Water Supply Network is a community of practitioners and academics focused on water in the developing world. The author reached out to this network by posting on their forums, and received a number of responses offering access to papers and case studies which are not available online. In addition to this, the organisation Excellent Development was contacted to request their sand dam manual (Maddrell and Neal, 2012), which they were willing to provide as well as a range of other reports and manuals.

### 2.1.2. Critique

The body of literature was then reviewed, and the quality of the sources was evaluated using a method put forward by Barker (2005). Here each source is evaluated on the factors laid out in Figure 8. This allowed for the filtering of the literature by discounting those which did not meet these conditions.

*Figure 8: Factors to evaluate the quality of academic sources*

**Authority** - Who is the author? What is their point of view?
**Purpose** - Why was the source created? Who is the intended audience?
**Publication & format** - Where was it published? In what medium?
**Relevance** - How is it relevant to your research? What is its scope?
**Date of publication** - When was it written? Has it been updated?
**Documentation** - Did they cite their sources? Who did they cite?

*[Source: Barker, 2005]*

This process resulted in a core of relevant and appropriate literature which could be used to input into the technical analysis in this research. In particular a subset of this core was chosen as a primary place with which to identify key criteria in sand dam feasibility. This subset has been listed in Table 1 with its source type and specific topic of interest.

*Table 1: Core literature used for sand dam technical analysis*

| Source | Year | Source Type | Country Focus | Genre | Specific Interest |
|---|---|---|---|---|---|
| Aerts et. Al | 2007 | Peer-reviewed journal | Kenya | Sand Dams | Resilience to Climate Change |
| Borst & de Haas | 2006 | Masters' thesis | Kenya | Sand Dams | Hydrology and Water Balance |
| Ertsen & Hut | 2009 | Peer-reviewed journal | Kenya | Sand Dams | Sustainability |
| Ertsen et al. | 2005 | Chapter in published book | Kenya | Sand Dams | Community Participation |
| Fewster | 1999 | Masters' thesis | Ethiopia | Sand Dams | Feasibility Study |
| Forzieri et al. | 2008 | Peer-reviewed journal | Mali | Ground-water Dams | Locating sites with GIS |
| Gezahegne | 1986 | PhD thesis | General | Ground-water Dams | Locating sites with GIS |
| Gijsbertsen | 1986 | Masters' thesis | Kenya | Sand Dams | GIS & sediment analysis |
| Hussey | 2007 | Manual for Practitioners | Zimbabwe | Sand Dams | Design and Abstraction |
| Hut et al. | 2008 | Peer-reviewed journal | Kenya | Sand Dams | Groundwater Levels |
| Jadhav et al. | 2012 | Peer-reviewed journal | India | Sand Dams | Needs Assessment |
| Jamali et al. | 2013 | Peer-reviewed journal | Sweden | Sub-surface Dams | Locating sites with GIS |
| Munyao et al. | 2004 | Manual for Practitioners | Kenya | Sand Dams | Construction & Operation |
| Maddrell & Neal | 2013 | Manual for Practitioners | General | Sand Dams | General |
| Nilsson | 1985 | Published Book | General | Groundwater Dams | Technical & Design |
| Nissen-Petersen | 2006 | Manual for Practitioners | Kenya | Sand Dams | Practical Implementation |
| RAIN | 2007 | Manual for Practitioners | Ethiopia /Kenya | Sand Dams | Practical Implementation |
| Stern & Stern | 2011 | Technical Briefing | General | Sand Dams | General |
| Van Heveren | 2004 | Peer-reviewed journal | Utah, USA | Groundwater Dams | General |

Each of these sources were reviewed systematically, drawing out key criteria in a matrix, with each source scored between 1 and 3 for each respective criteria based on how important the source considered that criteria, and the depth with which the source investigated that criteria, and the level of justification they gave. These criteria were then synthesised and amalgamated by the author, seeking to condense complex issues into concise and pertinent criteria. On account of size limitations for this research, it was decided to restrict the scope to focus exclusively on technical criteria, though there are also a range of other factors (socio-economic, political, and legal) which will also be key in determining sand dam feasibility (see Section 8.2). In this way the three key technical criteria, and their respective parameters were identified: Water Supply (Chapter 3), Storage Capacity (Chapter 0) and Affordability (Chapter 5)

As the technical analysis progressed, the author also looked into physical processes related to sand dams which had often not been covered extensively in the existing body of literature. This led to the need to draw on other literature beyond the literature listed above, which often was not immediately related to sand dams, but provided insight and research into the hydrological and climatic factors which impacted sand dam feasibility. A list of these additional 'technical sources' have been included in Table 2.

*Table 2: Technical sources for investigating sand dam feasibility*

| Source | Year | Source Type | Country Focus | Specific Contribution to Technical Analysis |
|---|---|---|---|---|
| BCEOM | 1978 | Technical Briefing | Africa | Evapotranspiration impact in arid lands |
| Bouma et al. | 2011 | Peer-reviewed journal | India | Rainwater harvesting and river discharge |
| Domenico & Schwartz | 1988 | Published Book | General | Hydrogeological processes |
| FAO | 2007 | Technical Briefing | General | Runoff Analysis |
| Hellwig | 1973 | Peer-reviewed journal | General | Evaporation rate from sand |
| Hoogmoed | 2007 | Masters' thesis | Kenya | Hydrology of sand dams |
| Linsley & Paulhus | 1958 | Published Book | General | Hydrogeological processes |
| Liu | 1998 | Peer-reviewed journal | General | Sediment erosion and transportation |
| Mein & Larson | 1971 | Technical Briefing | General | Groundwater infiltration |
| Mughal et al. | 2005 | Peer-reviewed journal | Saudi Arabia | Evaporation rate from sand |
| Olofsson | 2002 | Peer-reviewed journal | Sweden | Groundwater infiltration |
| Quilis et al. | 2009 | Peer-reviewed journal | Kenya | Modelling methods for sand dams |
| Rivas-Martinez | 2007 | Technical Briefing | Chad | Precipitation Analysis |
| Rosgen | 1994 | Peer-reviewed journal | General | River Classification |
| Sharma | 1986 | Peer-reviewed journal | General | Runoff Analysis |
| Smakhtin & Weragala | 2005 | Technical Briefing | Sri Lanka | Environmental Impact |

This therefore provides an overview of how the author critiqued and made use of the literature base. Chapters 3, 4 and 5 provide a very thorough analysis into the existing literature, and indeed go beyond so develop a feasibility framework for sand dams. However, prior to this, we will make a few key observations from the literature which will set the stage for what follows.

## 2.2. SAND DAM COMPARISON

Sand dam with their saturated sand ('underground storage') are comparatively less understood than conventional over-ground dams with reservoirs of water ('surface storage'). For small-scale projects in arid climates where conditions are suitable, the literature emphasises some significant advantages of sand dams over surface storage dams. These factors have been compiled from across the different sources, and all those factors mentioned in two or more sources are listed below in Table 3.

*Table 3: Advantage of sand storage dams above surface storage dams*

| | Al Taiee, 2010 | Borst & de Haas 2006 | Ertsen & Hut, 2009 | Ertsen et al 2005 | Gezahegne 2008 | Munyao, 2004 | Nissen-Petersen 2006 | Baurne 1984 | RAIN 2007 |
|---|---|---|---|---|---|---|---|---|---|
| Lower evaporation loss because there is no direct solar radiation | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Groundwater suffers less from contamination, pollution and littering | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ |
| Sand filtration means high water quality and low bacterial content | ✓ | ✓ | | | ✓ | | | | ✓ |
| Fewer mosquitos since there is no standing water for year round breeding | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| Less salinity in the water, since this is directly correlated to evaporation rate | | ✓ | | | ✓ | | | | |
| No submergence of land or destruction of property and habitats | | | ✓ | ✓ | ✓ | | | ✓ | |
| Less expensive both for construction and maintenance | | | | | ✓ | ✓ | | ✓ | ✓ |
| Promotes participation, making us of labour contribution from users | | | | | ✓ | ✓ | | | ✓ |

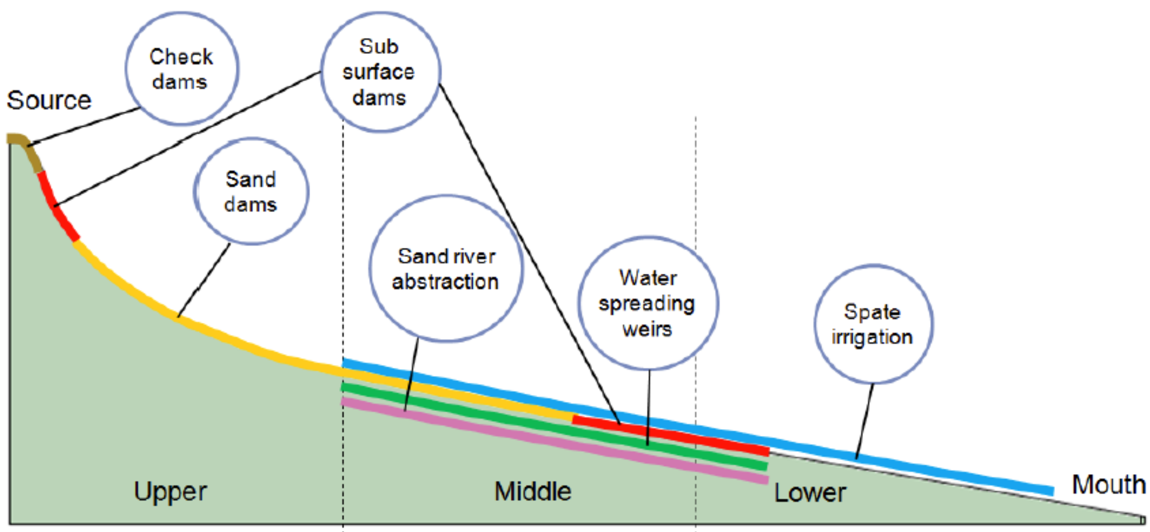
## 2.3. SAND DAM CLARIFICATIONS

Throughout the literature there is mixed usage of terminology to describe a range of different but related technologies, resulting at times in confusion or apparent contradiction; translation difficulties (primarily between England, French and Italian) exacerbate this. Van Haveren (2004:3) recognizes this difficulty and seeks to lists the range of technologies: "sub-surface dams, sand storage dams, check dams, trap dams, sponge dams, desert water tanks." Additionally there are also weirs, dykes, hafirs, etc. They share a high degree of overlap, since all are concerned with the interception and storage of surface run-off and groundwater behind a manmade dam in arid or semi-arid climates with highly seasonal precipitation (Nilsson, 1985). Notwithstanding these similarities, for the purposes of this research it is necessary to differentiate them, since each has different conditions which most suit it; they thus cannot be considered with equivalence. The most pertinent categorical differences are:

1) Whether the dams themselves are located underground, above ground, or both; and
2) Whether the dams are primarily designed to intercept surface run off, groundwater, or both.

These various technologies (and others) are also acknowledged by Maddrell & Neal (2012:66), and laid out with respect to river slopes in Figure 9 below:

*Figure 9: River channel profile with in-channel water technologies*




*[Source: Maddrell & Neal, 2012:66]*

In the last two decades, the two options that have been most widely referenced in the literature are sub-surface dams and sand storage dams (shortened to sand dams). Both are groundwater dams: structures providing storage of water underground by obstructing the natural flow of groundwater (Al-Taiee, 2010:35), in contrast to over ground reservoirs. As such a significant proportion of the available literature considers them together (e.g. Nissen-Petersen, 2014; VSF, 2006; Forzieri et al., 2008; Hussey, 2007; Nilsson, 1984). Whilst this may be suitable for some purposes, it is definitely not when it comes to considering feasibility and siting (Jamali et al., 2013; Nilsson, 1985). Sand dams are a specific sub-category of sub-surface dams, whereby they are located across the riverbed and provide greater water storage capacity by obstructing sediment transport to ensure an accumulation of coarse sands and gravel upstream of the dam (Al-Taiee, 2010:37).

This research has limited its scope to focusing exclusively on sand dams. This precludes a fuller analysis of the broader topic of groundwater dams generally, but this is offset by enabling a deeper study of sand dam feasibility without the need to incorporate related technologies which might otherwise water-down the usefulness of the final results. Nonetheless, this is somewhat impeded by the existing literature which often poorly delineates between these different technologies, often using terms interchangeably, even when the discussion is pertinent only to one or the other.

## 2.4. LITERATURE TRENDS

### 2.4.1. PRACTITIONERS V. ANALYSTS

The author has observed two different ‘lenses’ through which sand dam research has been undertaken to date, resulting in a somewhat polarized literature base:

- On the one hand, the practitioner approach draws from field experience or case studies to develop manuals for sand dam implementation (e.g. Borst & de Haas, 2006; Fewster, 1998; Hussey, 2007; Munyao et al., 2004; Maddrell & Neal, 2013b; Nissen-Petersen, 2006; RAIN, 2007; Stern & Stern, 2001). Whilst helpful in guiding grassroots initiatives in local contexts, such research lacks a systematic approach and full analysis for wider application. Furthermore, the literature arises from a fairly limited geographical sample, primarily from the Kitui region of Kenya, where sand dams have been extensively and successfully constructed, and reported on. It is dubious as to whether such findings are easily transferable to other contexts which are less geographically homogenous (such as eastern Chad).
- On the other hand, the analytical approach draws on hydrogeological and technical research using GIS data and remote imaging across whole regions, to investigate sand dams against various prescribed parameters (e.g. Aerts et al., 2007; Ertsen & Hut, 2009; Forzieri et al., 2008; Gijsbertsen, 2007; Hoogmoed, 2007; Hut et al., 2008). Whilst very insightful for understanding how sand dams interact with dynamic physical processes - groundwater flow, sediment transport and bedrock characteristics – the research provides limited application for siting and design and remains un-synthesized with field-based surveying and proper handling of socio-economic factors pertaining to long-term sustainability.

The author is not satisfied that existing research has succeeded (and in most cases not attempted) to bring together these two strands under a single holistic framework to assess sand dam feasibility. This paper attempts a preliminary handling of such a task, marrying the empirical data of field-based practitioners with the analytical findings of desk-based investigations.

In particular, the practitioner approach starts with the local stakeholders, and places the community firmly at the middle of decision-making regarding the sand dam suitability and its prospective siting. The rationale for this bottom-up approach is that it ensures a high level of community engagement which encourages participation in sand dam construction as well as long-term ownership leading to greater sustainability (Munyao, 2004;10; Stern & Stern, 2001:16). Excellent Development's sand dam manual, which is the most high-profile of many publications which typify this approach, states explicitly: "the community decides on the most appropriate option for them… the first step in applying sand dam technology is to talk with the communities to establish their needs and to establish that in their opinion a sand dam is the most appropriate solution" (Maddrell & Neal, 2013b). The implicit assumption here is that the 'starting point' for assessing sand dam suitability must be the local community. This reflects both an implementation bias (community-centeredness) as well as an assumed regional hydro-geological suitability. Some even presume that such research is not available, stating wrongly that ""on the hydrology of sand dams very little is known" (Al-Taiee, 2010:36). Other literature does acknowledge the role of analysis by technicians in the decision-making process, exemplified by an NGO in Kenya (SASOL) working with local communities:

> "*Dam siting… is a combined activity of the community and SASOL technicians. SASOL asks the community to indicate a number of favourable locations for a sand storage dam, based on hardrock outcrops, bank stability, walking distance and land ownership. The community is let to select the locations. After a week or so SASOL personnel returns to the community, walks with them through the river and reviews the locations selected by the community. Based on this review a location is selected."* (Borst & de Haas, 2006:42)

However, even here, as elsewhere, there are some assumptions based on operational biases:

> <u>Assumption #1</u>: The regional context is appropriate for sand dam construction. This may be inferred if the region already has many sand dams constructed, but for other contexts this represents a major 'jump' in feasibility, which is usually inadequately investigated by practitioners in their literature.
>
> <u>Assumption #2</u>: That sand dams are the most appropriate technology for the context. This is a common bias in development practice, since NGOs are often constrained by project plans and expertise/capacity limitations, such that a particular technology is necessarily pre-selected, prior to considering the specific context or involving the community.
>
> <u>Assumption #3</u>: That all communities can identify a suitable sand dam site. The bottom-up approach engages communities from the outset, and thus establishes an expectation, or at

> very least pressure, to deliver a sand dam. However, sand dams are only appropriate in certain conditions; where these are not present other water resource options are preferable.

Since sand dams have a track record of providing viable and cost-effective water solutions for rural communities, many practitioners write to advocate rather than to critique, and infer that sand dams are easy to site and implement. However Gijsbertsen contests this: “good location for sand storage dams meets a set of local and environmental criteria. Not all of these criteria are known and are nowadays partly underestimated during siting of locations, resulting in minor efficiency of constructed dams” (2007:16).

This provides a pertinent backdrop for the analytical approach, which typically employs a technical analysis of the whole region to firstly consider sand dam viability, and may also propose favourable locations based on probability algorithms. This ensures a thorough handling of technical factors, including climate, geology, environment and topography. Gezahegne (1986:6) sets out a basis for this approach: “the topographical conditions govern to a large extent the technical possibilities of constructing the dams as well as achieving sufficiently large reservoirs with suitable recharge conditions and low seepage losses.” However, analytical approaches are impeded by poor data quality (e.g. satellite resolution) and spurious results deriving from large error bars and anomalies (Hoogmoed, 2007). Findings benefit from field-based point surveys which collect local geological and environmental data (Forzieri et al., 2008:75). However, even though this improves the results, the paradigmatic distance between this approach and that of practitioners is exposed by the fact that such surveys invariably fail to incorporate any community factors – local needs, willingness to pay and proximity of water source to water users – in their data collection and subsequent recommendations.

### 2.4.2. Macro, mid and micro levels

Firstly, this body of research seeks to synthesize these divergent approaches through a multi-layered analysis, which is then applied to the Chadian context. There are typically three layers on which sand dam feasibility study should take place:

1) Macro/regional analysis: first the whole region/country is considered to establish whether there is the right enabling environment (physical, but also social-economic and political/legal).
2) Mid/catchment analysis: the local surroundings (e.g. stretch of riverbed and its catchment) is considered, looking at hydrogeology suitability, local communities and livelihoods.
3) Micro/siting analysis: the specific siting needs to be determined by identifying favourable locations for the sand dam; this must involve community participation and input so that there is ownership of the outcome of this analysis by the local stakeholders.

Many practitioners (e.g. concerned with building just one dam) will want to start with the mid and micro analysis (establish a viable community and location), but should also be conscious of the macro analysis, since for wider sand dam building initiatives it is critical to first look at the overarching factors for a whole region, to ensure a viability which then justifies a more field-based analysis of mid and micro factors. Conversely, a focus on the macro analysis must not belittle the indispensable local engagement and local factors that are necessary for success.

The technical analysis in Chapters 3, 4 and 5 draw out a wide range of parameters for sand dam feasibility which need to be categorized. The above (macro/regional, mid/catchment, micro/siting) is one tool which can be applied for this purpose.

### 2.4.3. CRITERIA V. INDICATORS

The second paradigm distinguishes underlying criteria from indicators. Some research, especially those looking at hydrogeological and environmental processes, isolate underlying criteria for sand dam favourability, such as an impermeable bedrock beneath the riverbed. Other research, often based on tests conducted during field visits, expresses the same parameter in terms of identifiable indicators ('symptoms'), such as the presence of scoop-holes in the riverbed and vegetation on the riverbank establishing that the bedrock beneath is indeed impermeable. Both are relevant but for different reasons: the first provides a fundamental basis for suitability (criteria); the second provides a means of testing it in a given context (indicator). This research looks at these parameters sequentially, first exploring the underlying criteria and seeking to understand the physical and economic processes motivating its pertinence, and second considering indicators which can applied during field assessment.

## 2.5. FRAMEWORK FOR TECHNICAL ANALYSIS

### 2.5.1. NOT UNIVERSALLY APPLICABLE

The next three chapters (3, 4 and 5) draw on the literature base to provide a technical analysis of sand dams and to synthesise this into a framework of criteria and parameters for sand dam suitability. This will thus answer research question 1. However, an underlying axiom of this research is that sand dams are not universally applicable (Al-Taiee, 2010:35) but rather there exists some contexts which are more appropriate than others. As such, sand dams should be considered as one of several appropriate technologies (Schumacher, 1973), within an integrated approach to the management of water resources. Criteria for sand dam suitability should therefore not be approached as a dichotomy, in search of a 'yes' or 'no'; the issues at stake are too multifaceted and interconnected for this. Rather, suitability falls on a multi-axis spectrum comprising multiple dependent variables (parameters) which cannot be neatly summarized as a list of 'yes, no' checkboxes. There is no holy grail for sand dam practitioners, but rather a negotiated way forward which holds in tension interrelated factors. This is corroborated by Gijsbertsen:

> *"Not all sand storage dams seem to work properly and apparently not all areas are suitable for the construction of these dams. The successful functioning of sand storage dams is dependent on a large amount of factors, including geology, geomorphology, precipitation and needs. These factors are in many cases unknown"* (2007:7)

In this vein, the technical analysis does not provide a panacea, but rather guiding principles, condensing parameters into conditions which must be explored and satisfied to aid decision making.

### 2.5.2. Criteria, parameters and conditions

From the breadth of the literature, and based on a 'common sense' approach, three overarching **criteria** have been identified with which to assess the technical feasibility of sand dams:

4. **Water Supply**: "sufficient supply and retention of water to ensure sand dam reservoir capacity is fully utilized."
5. **Storage Capacity:** "maximal and suitable water storage capacity available in the sand dam reservoir."
6. **Affordability:** "the sand dam is affordable, both initially in construction and long-term in its sustainability."

In each case the underlying processes and factors affecting these criteria are explored and explained, with relevant **parameters** identified which affect the criteria's suitability. Each of these parameters comprises a number of **conditions** which need to be satisfied. Though this approach does not claim to be completely comprehensive, it does provide a more substantial and reasoned tool for assessing sand dam suitability than is currently available in literature.

Within the analysis, regular reference is made to the different paradigms introduced in Section 2.4. This includes an awareness of the different starting points of 'practitioners' and 'analysts' as well as sensitivity to the difference between criteria and indicators. Additionally, the criteria analysis requires that for a full sand dam feasibility study to be undertaken, assessments must be made both on a macro/regional level, and also be reinforced by mid/ catchment level assessment, with local field visits conducted to identify prospective sand dam sites. These three levels of data collection and analysis need to be undertaken to provide inputs for this framework.

# 3. WATER SUPPLY

Criteria 1: sufficient supply & retention of water to ensure sand dam reservoir capacity is fully utilized.

Sand dam viability depends on supplying users with the water quantity they need (Forzieri et al., 2008:74, Nissen-Petersen, 2006:12). This is challenging given that sand dams are designed for arid regions "where potential evaporation is larger than rainfall," (Nilsson, 1984:12). However, the very rationale for sand dams is derived from the fact that surface water is not available year round, requiring the damming of groundwater in riverbeds to enable abstraction (Gezahegne, 1986:4; Al-Taiee, 2010:35). The rivers across which sand dams are constructed are usually ephemeral: they "flow for short periods in direct response to precipitation" (Gijsbertsen, 2007:17). This prompts the basis for constructing sand dams (availability of water storage and ease of abstraction during dry seasons) as well as the main challenge to their viability (necessity of sufficient water input during the rainy season, and minimal water loss through seepage, so as to ensure perennial water availability).

Thus this water supply criteria has two core components:

I. Sufficient water supply ensures that at the start of each dry season the sand reservoir behind the sand dam is filled with water.
II. Minimal water loss from the reservoir ensures efficient water storage during dry season and its availability for abstraction and use.

## 3.1 WATER BALANCE

The water balance equation provides a suitable framework to look at these two related components, with insight into various fluxes and quantities in the system (Borst & de Haas, 2006:70). We define $Q_{in}$ as the input, $Q_{out}$ as the output, and $\Delta S$ as the change in storage, all with reference to the sand reservoir behind the sand dam. Thus:

$$\Delta S = \int_{t=0}^{t=\Delta t} Q_{in} - Q_{out}.dt$$

Between the start of successive dry seasons, storage is constant (i.e. water fills the reservoir at this time). Thus when $\Delta t$ is the timeframe between the start of dry seasons, $\Delta S = 0$. The system is in equilibrium and can be expressed as follows:

$$Q_{in} = Q_{out}$$

The input and output can be expressed with set of equations (ibid.), as illustrated in Figure 10, where all parameters have the same dimension, volume of water:

$$Q_{in} = R + B = P - E_T - G_c$$
$$Q_{out} = Q + L + G_r + E + U$$

Where:

$P$ – precipitation (m$^3$),

$E_T$ – evapotranspiration (m$^3$)

$E$ – evaporation from sand reservoir (m$^3$)

$G_C$ – groundwater infiltration, catchment (m$^3$)

$G_R$ – groundwater infiltration, riverbed (m$^3$)

$Q$ – river discharge when in flow (m$^3$)

$L$ – leakage from the sand reservoir (m$^3$)

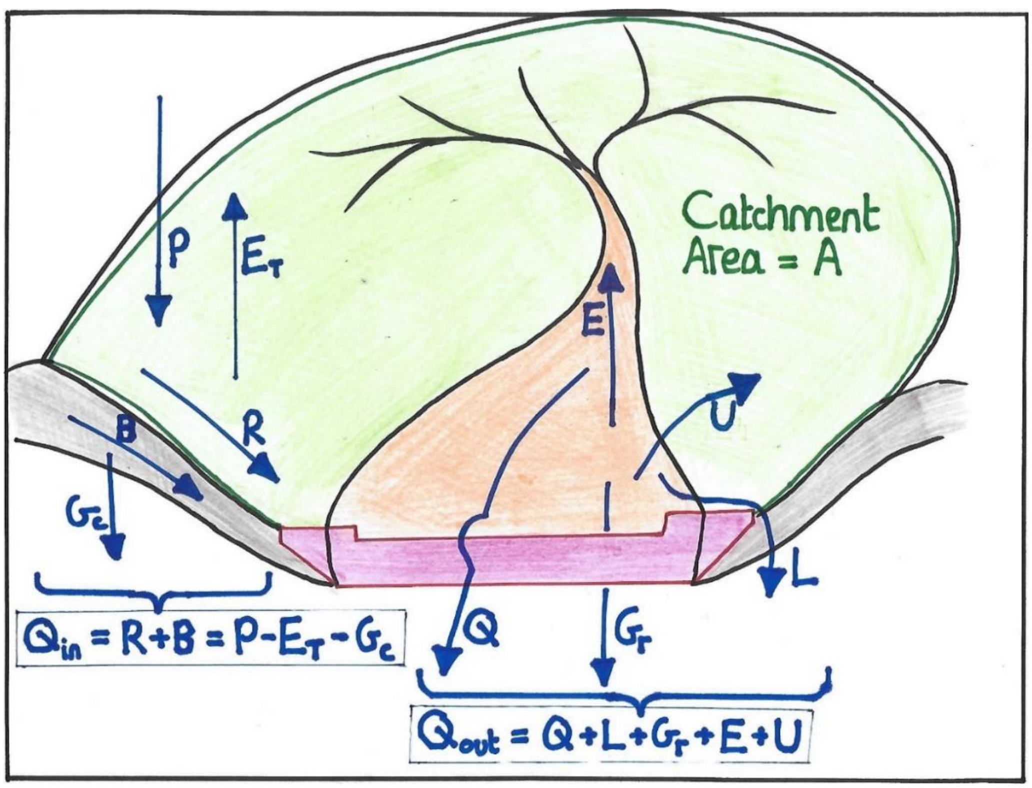
$U$ – abstraction by water users (m$^3$)

$R$ – runoff in the catchment (m$^3$)

$B$ – lateral baseflow through catchment (m$^3$)

N.B. $L$ is used for leakage that flows horizontally either under the dam or through the riverbank and around the dam; conversely $G_R$ is the water loss that occurs vertically from the riverbed into the deep aquifer by means of groundwater infiltration.

*Figure 10: Water balance variables for sand dams*




*[Adapted from: Borst & de Haas, 2006:70]*

The water balance equation provides a framework to consider the two components above:

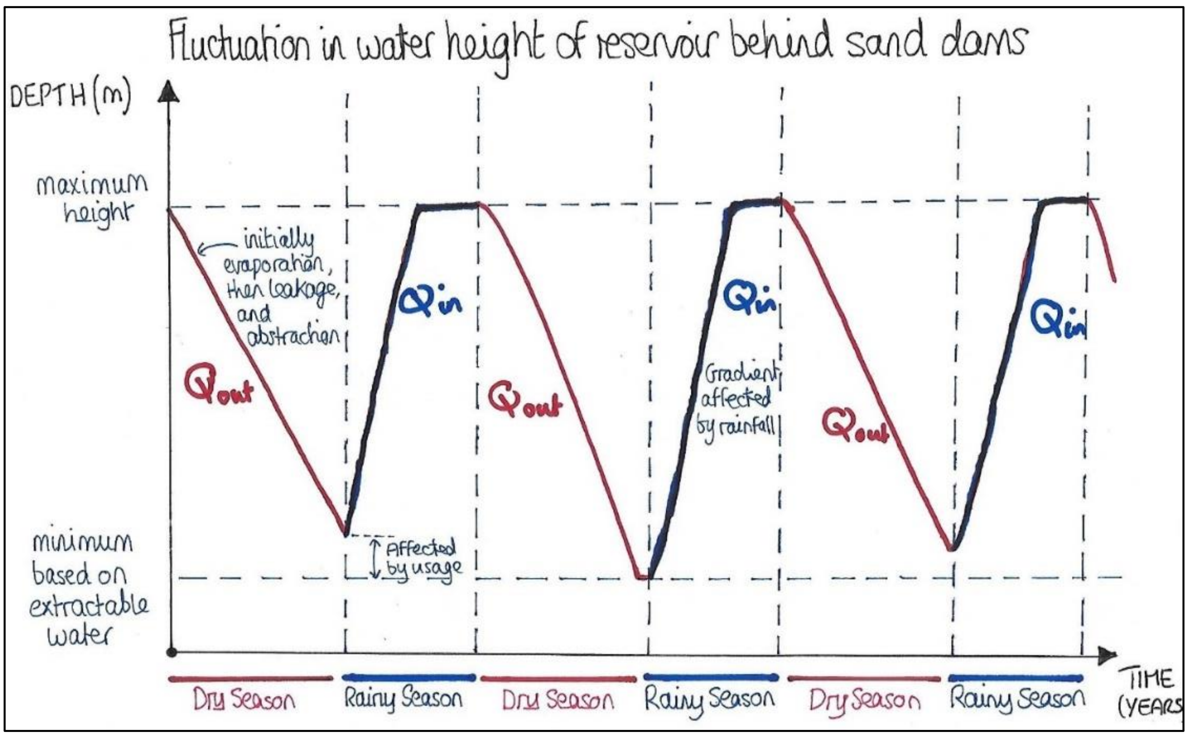
I. To ensure sufficient water supply, $Q_{in}$ must meet a context-dependent minimum threshold ($Q_{min}$) during the rainy season, i.e. $Q_{in} \geq Q_{min}$. For a specific location we must both determine the value of $Q_{min}$ and use this then calculate a probabilities for whether the input, $Q_{in}$, meets this threshold in a given year.

II. To ensure water loss during dry season is at tolerable levels, a sufficient proportion of $Q_{out}$ must be available for abstraction, $U$ i.e. $U \geq \alpha . Q_{out}$. Given that $Q = 0$ (ephemeral rivers do not flow during dry season), $L$, $G_r$ and $E$ must be low enough to satisfy the following condition:

$$L + G_r + E \geq \beta . U \quad \text{where } \beta = \frac{1-\alpha}{\alpha}$$

The seasonal fluctuation of water height behind the sand dam can be seen in Figure 11 below:

*Figure 11: Seasonal fluctuation of water levels in the sand reservoir*




We will now consider these many variables in turn, starting with infiltration and impermeability.

## 3.2 IMPERMEABILITY

The vertical percolation of water through bedrock and infiltration into deep aquifers below will impact the water supply, and relates to both $G_c$ and $G_r$ in the following ways:

- The groundwater infiltration across the whole catchment ($G_c$) affects the amount of water available to input into the sand reservoir during rainy season;

- The groundwater infiltration rate under the riverbed ($G_r$) affects the speed of water loss from the sand reservoir and thus the abstractable volume from the sand dam during dry season.

The literature base is unequivocal that reliable sand dam water supply requires that the bedrock beneath be impermeable (Maddrell & Neal, 2012:10). Impermeability avoids "seepage of water into the deeper layers" (Ertsen et al., 2005:4). Failure to acknowledge the importance of impermeability undermines sand dam success:

> *"Since the construction of [these] dams is a rather straightforward affair and inexpensive, often no technical investigations are made as regards geology and hydrogeology. As a result, there are unfortunately many examples [where they] have not been successful due to lack of good investigations… caused by unforeseen seepage losses through underlying fracture zones and erosion damages due to improper bed rock foundation." (Gezahegne 1986:13)*

The rate of infiltration is determined by two different aspects of the morphology of the ground:

- How easily the water flows through the medium, called hydraulic conductivity;
- How much cracking and fractures there is, along which water can flow.

The hydraulic conductivity of a medium is calculated by Darcy's Law applied to the bedrock (Munyao et al., 2004:26-27):

$$Q_{flow} = K.A.i \qquad where \quad K = \frac{k\rho g}{\mu}$$

Where:

$Q_{flow}$ – Flow rate through the material ($m^3s^{-1}$)
$K$ – Hydraulic conductivity in flow direction ($m^2$)
$A$ – Cross-sectional area of material ($m^2$)
$i$ – Hydraulic gradient in flow direction (Pa)
$k$ – Intrinsic permeability ($m^2$)
$\rho$ – Density of the liquid ($gm^{-3}$)
$g$ – Acceleration due to gravity ($ms^{-2}$)
$\mu$ – Dynamic viscosity of the material (Pa.s)

Darcy's Law can be applied to various types of bedrock to calculate their hydraulic conductivity (Olofsson, 2012; BCEOM, 1978; Hoogmoed, 2007, Munyao et al., 2004). This is synthesized with the fracture characteristics of the bedrock to provide categorization of the bedrock in terms of their permeability. This was comprehensively undertaken by Lewis et al. (2006) in their British Geological Survey report, "Guide to Permeability Indices". It summarises overall permeability of different rock types by combining the hydraulic conductivity calculations (above) with the impact of fractures and cracks in the rock, to develop the framework in

Table 4.

*Table 4: Permeability categories for a range of bedrock types*

| Lithology (Bedrock) | Predominant Mechanism | Maximum Permeability | Minimum Permeability | Sand dam Feasibility – Is it suitable? |
|---|---|---|---|---|
| Gravel | Intergranular | Very high | Very high | No |
| Sand | Intergranular | High | High | No |
| Silt | Intergranular | Moderate | Moderate | No |
| Clay | Mixed | Low | Very Low | Yes |
| Limestone | Fracture | Very High | Moderate | No |
| Sandstone | Mixed | High | Low | Maybe |
| Mudstone | Fracture | Low | Very Low | Yes |
| Granite | Fracture | Moderate | Low | Maybe |
| Trachyte | Fracture | Moderate | Low | Maybe |
| Gneiss | Fracture | Low | Low | Yes |

*[Adapted from: Lewis et al., 2006:9]*

*For the purposes of sand dam feasibility, it is rarely worth undertaking detailed on-site analysis to estimate bedrock permeability (Gijsbertsen, 2007). Rather, a summary approach should be taken, by finding geological data about the region (often from hydrogeological maps), and using this to classify the bedrock in accordance with*
Table 4. This provides a basic decision-making framework:

- Certain types of bedrock (gravel, sand, silt, limestone) are unfavourable for sand dam water supply: they have moderate to high permeability so significant water loss will occur through $G_c$ and $G_r$;
- Certain types of bedrock (clay, mudstone, and gneiss) are considered favourable for ensuring water supply to sand dams, since they have low or very low permeability, so $G_c$ and $G_r$ will be negligible.
- Certain types of bedrock (sandstone, granite, and trachyte) have a range of permeability values, a portion of which would be considered favourable for sand dams. Further analysis is required to determine their suitability for sand dams.

Infiltration vertically from the sand reservoir ($G_r$) is usually far more concerning than groundwater infiltration $G_c$ across the whole catchment area. Where there is high volume of available runoff, $R$, the vast majority of the input, $Q_{in}$, is lost as unneeded river discharge ($Q$). Thus rate of groundwater infiltration across the catchment will not affect water supply to the sand dam. Only in contexts where rainfall is very low indeed and when the runoff coefficient (see below) is low would it become statistically significant. Such situations are considered in more depth with respect to rainfall in Section 3.7.

By contrast, the rate of infiltration into the bedrock from sand reservoir directly beneath the riverbed is of far greater consequence. Each litre of water lost in this manner represents one litre less of abstractable water from the sand dam. Since such infiltration occur continually across the whole dry season without replenishment, its impact is compounded by virtue of its incessancy. This is further exacerbated by the fact that fractures are more likely geologically to be located at the base of valleys where the sand reservoir is located. For this reason Forzieri et al. (2008:80) state succinctly: "the sites with [fractures] along streams must be eliminated from potential sites list." Gezahegne illustrates its pertinence:

> *"One example is the first sand dam constructed at Gende-Balina in… Ethiopia. The dam was constructed in 1983, but has not come into operation due to unforeseen seepage losses. This is because no geological investigations were made to identify underlying fracture zones."* (Gezahegne, 1986:13)

*Thus, with reference to*
Table 4, those categories of bedrock which have a broad range of possible permeability spanning both the favourable and unfavourable needs to be analysed further. The reason for the range is that its permeability is the possibility of fracturing and cracking, which is specific to each location and thus cannot be determined generically (Lewis et al., 2006). As such at the mid/catchment level the probable location of fractures needs to be identified. These are available from hydrogeological maps, or if necessary can be derived with GIS algorithms and remote imaging data (Gijsbertsen, 2007; Hoogmoed, 2007). Though fractures do not necessarily mean water loss (some can themselves be impermeable) it is very hard to know. Even where it does not currently cause water loss through infiltration (perhaps evidenced by scoop holes and widespread vegetation along the river), it cannot be known whether that will remain so when additional head of pressure is applied by the sand reservoir. The presence of a fracture or possible fracture beneath the riverbed should automatically discount the site from consideration for sand dam construction.

A desk-based study of fracture location should be followed up by a field visit to provide an even clearer view. Local knowledge about which riverbeds, and where in the riverbed, water is naturally found is of great value. The presence of 'scoop-holes', which local communities historically rely upon for water collection during dry seasons, strongly suggests impermeability beneath a riverbed (Munyao et al., 2004:12). It is further recommended to survey the prospective site at the end of dry season to measure the water depth of the riverbed for insight into the impermeability of the bedrock underneath. This is reflected in RAIN's guidelines:

> *"Presence of waterholes especially after the rainy season is an indication that the riverbed contains water and that it does not leak to deeper groundwater very fast. Pay special*

*attention to those providing water the longest during the dry season. Also note the depth of the water table to the riverbed surface."* (RAIN, 2007:11)

Thus the further analysis required for certain types of bedrock (sandstone, granite, trachyte) can be conducted on these terms: first verify that there is no fracture under the riverbed and second check for the presence of scoop holes in the riverbed, and/or water remaining throughout the dry season.

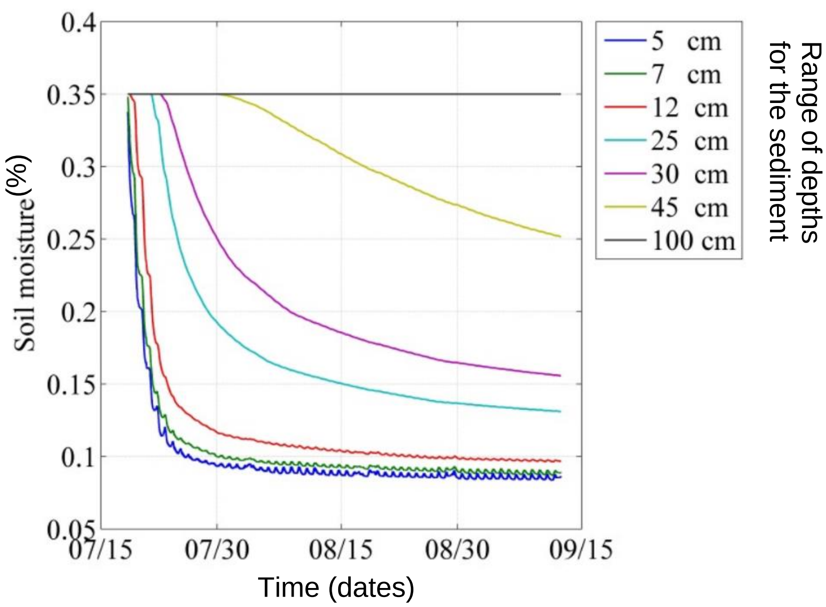
## 3.3 EVAPORATION

Evaporation, $E$, is defined as the evaporation of water in the sand reservoir during dry season. Water is vulnerable to loss by evaporation in light of the high temperatures of arid climates; we need to understand better the physical processes and factors which impact this variable. Hellwig (1973) studied how depth of water table and grain size impacts evaporation from sand. He found:

- When the reservoir is saturated (i.e. water level is at surface) the evaporation rate is 8% lower that it would be for open water, irrespective of the grain size of the sand.
- As the water table drops the rate of evaporation depends on grain size, with higher rates in fine sand than coarse sand.
- Evaporation ceases almost completely when the water table reaches a depth of 60cm.

*Figure 12: Soil moisture change over time for different depths of sand*

**The moisture of soil over two months at different depths for sediment with porosity 0.35%**




*[Source: Mughal et al., 2005:12]*

To calculate the total volume of water that evaporates from the sand reservoir we can draw from research undertaken by Mughal et al. (2015). They conducted experiments of total evaporation from coarse sand in arid conditions (Saudi Arabia), by measuring the moisture of sand (with porosity 25-45%) at different depths over a period of two months, shown in Figure 12.

We can draw from this graph some patterns using a step-wise analysis for various ranges of depth, which provides some simplified calculations for our purposes:

$$For\ depths\ of\ \begin{cases} 0-25\ cm \\ 25-45\ cm \\ 45-60\ cm \end{cases} soil\ moisture\ content\ tends\ to\ approx. \begin{cases} 10\% \\ 20\%. \\ 25\% \end{cases}$$

$For\ depths\ over\ 60cm, negligible\ water\ loss\ occurs$. (Hellwig, 1973).

We can thus estimate total water loss from sand reservoir through evaporation, with porosity $n$:

$$E = (n-10\%)V_{0-0.25} + (n-20\%)V_{0.25-0.45} + (n-25\%)V_{0.45-0.60}$$

$$E = n.V_{0-0.60} - 0.1V_{0-0.25} - 0.2V_{0.25-0.45} - 0.25V_{0.45-0.60}$$

Where $V_{b-a}$ is the total volume of sand in the sand reservoir with depth ranging from a to b, and $n$ is the porosity (%) of the sand. This assumes uniform porosity of the coarse sand within the ballpark of 35% ($0.25 < n < 0.45$), and that every square meter of sand across the whole area of the sand reservoir, $A_{storage}$, has a minimum depth of 60cm, the total evaporation can be estimated:

$$V_{0-60} = 0.6.A_{storage}$$

$$E = [n.(0.6-0) - 0.1(0-0.25) - 0.2(0.45-0.25) - 0.25(0.60-0.45)].A_{storage}$$

$$E = (0.6.n - 0.1025).A_{storage}$$

For a given porosity of coarse sand ($0.25 < n < 0.45$) the evaporation is directly proportional to the area of the sand reservoir. This will admittedly be a slight overestimate, since some of the sand area will have a depth of less than 60cm, but this is offset by the small amount of evaporation that occurs at a depth deeper than 60cm which we have not factored here.

The most straightforward way to acknowledge the impact of this evaporation on the volume of water stored is to discount a top layer of the sand reservoir with height, $h_{sand}$, which would contain water of volume $E$.

$$E = n.h_{sand}.A_{storage} \quad \Rightarrow \quad h_{sand} = \frac{E}{n.A_{storage}}$$

$$h_{sand} = \frac{1}{n}(0.6.n - 0.1025) = 0.6 - \frac{0.1025}{n}$$

This gives us a 'usable' storage capacity for the sand reservoir, and allows us therefore to ignore the effects of evaporation, i.e. $E = 0$. This top layer is discounted in calculating the volume of water in the dam in Section 4.1. This may render the sand dam less suitable given a reduced volume of abstractable water in light of evaporation. This analysis is corroborated by Borst & de Haas's approximation (2006:68): "Part of the water will evaporate from the sand. Since evaporation is decreased by over 90% when the water level is at 60 cm below the sand surface, evaporation will only take place if the water level is less than 1 m below sand surface." Furthermore, Maddrell and Neal (2012:14) likewise acknowledge that the upper layer of the sand reservoir should be ignored.

## 3.4 LEAKAGE

Finally the leakage, $L$, needs to be evaluated as part of our investigation into water loss. However, this is somewhat more straightforward to handle here, since the extent of leakage is typically a function of the quality of design and construction of the sand dam, and is less linked to characteristics intrinsic to the location. Gijsbertsen (2007) tackles this by advocating greater attention to detail in sand dam implementation, in particular related to the reduction of seepage immediately underneath the dam wall by tailoring construction methods to suit the type of bedrock upon which it is sited. This may affect the affordability of the sand dam (see Chapter 5) which may disqualify it from suitability, but here our concern is water loss by seepage under and around the dam. This can invariably be addressed by good construction methods, as described in many places in the literature (e.g. Munyao 2004:12; Nissen-Petersen, 2006; Stern & Stern, 2011; Maddrell & Neal, 2012).

We thus have a framework for minimizing water loss:

- By setting impermeable bedrock as a pre-requisite for sand dam suitability, $G_r = 0$.
- By surrendering a top layer of the sand reservoir to evaporation, at the expense of the inevitable storage capacity, we eliminate effects of evaporation; we can consider $E = 0$.
- By attributing leakage to human error rather than environmental factors, we can stipulate the necessity of appropriate design to ensure a minimization of leakage, thus $L = 0$.

On these terms we have a functional 'exclusion' to the water loss factor in all further analysis.

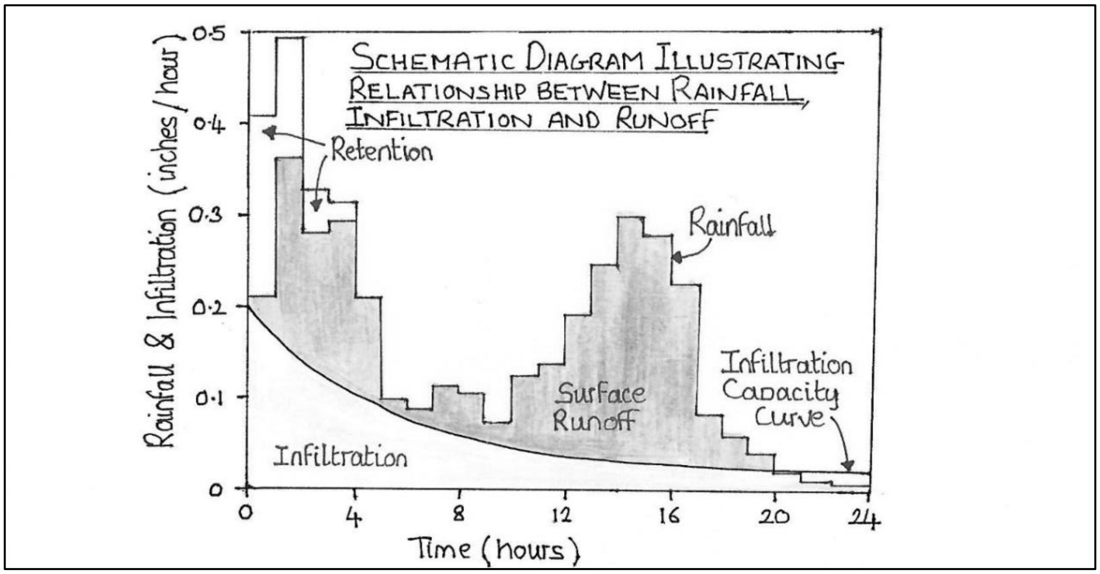
## 3.5 RUNOFF

The water supply to the sand reservoir is made up of runoff and baseflow: $Q_{in} = R + B$. By way of clarification, baseflow refers only to that which occurs through the catchment, and not the baseflow through the riverbed (which is obstructed by the dam). Much of the literature simplifies this by assuming that none of the water which infiltrates the soil reaches the river i.e. that $B = 0$. , This is usually legitimate, since arid climates' high levels of evapotranspiration mean baseflow is typically small (Borst & de Haas, 2006). Thus we have a more straightforward formulation whereby water supply into the sand reservoir is accounted for by runoff.

$$Q_{in} \approx R$$

Runoff is contingent on multiple rainfall and geological conditions (Hoogmoed, 2007:17). During rainfall, the first drops of water are intercepted by organic matter, known as interception storage or retention. As such greater vegetation density means less runoff (FAO, 2007:8). The remainder reaches the ground surface and begins to infiltrate the soil. Only when the rate of rainfall is greater than infiltration capacity is runoff generated, as demonstrated in Figure 13, which shows how varying rainfall intensity interfaces with infiltration and runoff, and Figure 14, which shows the relationship between infiltration and runoff over time for a constant rainfall intensity.

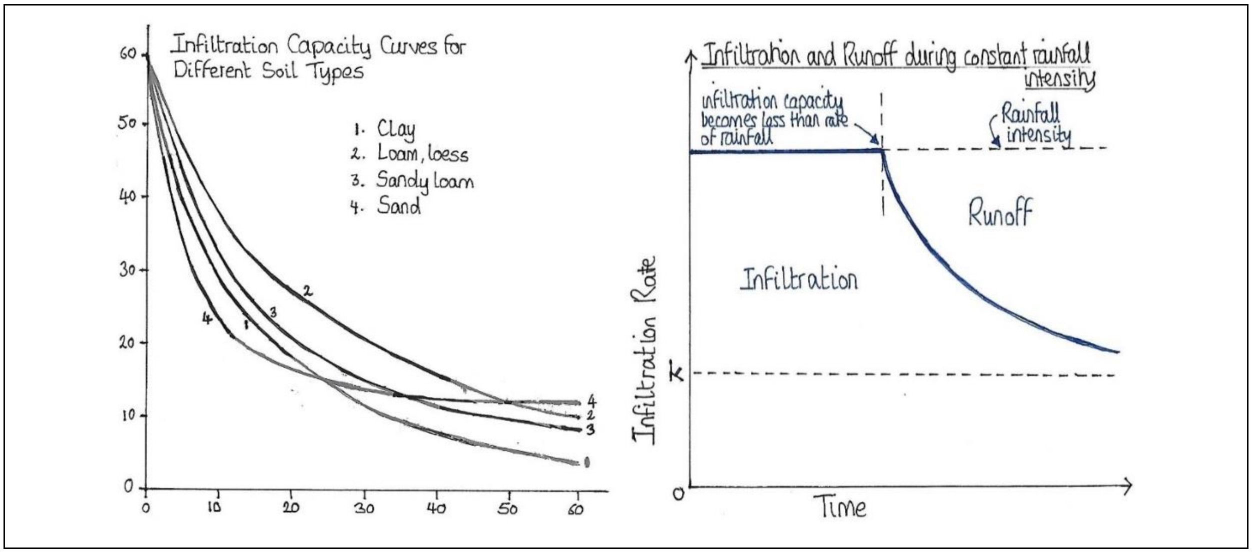
*Figure 13: Schematic of relationship between retention, infiltration and runoff*




*[Adapted from: Linsley & Paulhus, 1958:8]*

Figure 13 above illustrates of what happens during a storm. The rainfall in the first hour is 0.4 inches, of which 0.2 inches is retained in vegetation, and 0.2 of which infiltrates into the ground; very little flows as runoff initially. However, it can be seen that as rainfall continues water is no longer retained in vegetation and similarly the rate of infiltration into the ground decreases as it too slowly becomes saturated, as illustrated in the right hand graph below in Figure 14. As the rainfall continues a higher proportion of it flows as runoff, thus demonstrating the significance of storm events (with higher rainfall) in contributing to high rates of runoff. By contrast if only light rainfall occurs then runoff will not take place.

*Figure 14: Graphs showing infiltration for soil types and infiltration rate against time*




*[Adapted from: Mein & Larson, 1971]*

The infiltration capacity depends on the porosity of the soil as well as the existing moisture content at the onset of the storm. It typically starts with a high value and then drops logarithmically to tend towards a ‘saturated’ constant (see Figure# above). However, often the soil surface will be disturbed (especially from high kinetic energy derived from large raindrops during storm events) whereby the soil aggregate is broken down and its fine particles are driven into larger pores. This results in a ‘capping’ effect: clogging up of pores and the formation of a compacted and less porous top layer which dramatically reduces infiltration (FAO, 2007:3.5.2.). In arid climates with sparse vegetation this can be a very major contribute to increased rates of runoff.

Catchment characteristics also have a major effect on runoff. Sharma (1986) observed that steep slopes yield more runoff than gentle slopes. Furthermore, as catchment area increases, runoff efficiency (volume runoff per unit area) decreases (Asher, 1988). In light of all these above factors, runoff will not as some claim be directly proportional to rainfall, and neither can runoff data be easily applied from one region to another (FAO, 2007:3.6.). In the context of sand dams, the relationship between runoff and rainfall is required not on a ‘storm-by-storm’ basis, but rather on an annual basis. This diminishes complexity by normalizing factors unique to each storm event. On this basis it is legitimate to perform linear regression analysis (ibid.), and express annual runoff in the following terms:

$$R = \kappa . P + c$$

The constant term, $c$, is crudely a ‘runoff hindrance’ constant which acknowledges the impact that variations in rainfall intensity and distribution have on runoff. This constant is always negative, since only the ‘perfect system’ (constant rate of rainfall across the whole year) returns $c = 0$. Likewise, $\kappa$ is the runoff coefficient specific to a given catchment/region, determined by morphology and soil conditions, including the capping effects mentioned above. This formulation is applied and shown to be suitable in numerous semi-arid and arid contexts (BCEOM, 1978:38).

## 3.6 EVAPOTRANSPIRATION

Evapotranspiration is the volume of water which is transferred from land back to the atmosphere as a result of evaporation from soil and transpiration from vegetation. There are multiple variables which impact evapotranspiration rates, but two most significant are (1) heat from solar radiation and (2) water availability in the soil. Potential evapotranspiration is the rate of evapotranspiration under conditions where water is not a limiting factor (Borst & de Haas, 2006:49). Numerous formulas are available to estimate it, the best known of which is Penman-Monteith's equation for potential evapotranspiration rate, $E_{T_0}$, which in a simplified form is expressed as:

$$E_{T_0} = \frac{\delta H + \gamma E_a}{\gamma + \delta}$$

Where:

$H$ – Net solar radiation above the crop surface (MJ $m^{-2}$ $day^{-1}$)
$\delta$ – Vapour pressure gradient (kPa $°C^{-1}$)
$E_a$ – Evaporative power of the air (kPa) i.e. saturation vapour pressure deficit
$\gamma$ – Bowen's constant

We are typically looking for annual evapotranspiration, rather than the daily fluctuations based on constantly changing conditions. In light of this it is appropriate to use the more straightforward Turc formulation (BCEOM, 1978) to calculate potential evapotranspiration in a given month, which can then estimate the actual evapotranspiration of the catchment area under consideration:

$$E_{T_0} = \begin{cases} 0.0133\,\dfrac{T_m}{T_m + 15}(R_s + 50) & \textit{where } RH > 50\% \\ 0.0133\,\dfrac{T_m}{T_m + 15}(R_s + 50)\left(1 + \dfrac{50 - RH}{70}\right) & \textit{where } RH < 50\% \end{cases}$$

Where:

$RH$ – relative humidity (%)
$T_m$ – Mean daily air temperature ($^oC$)
$R_s$ –Incoming solar radiation (mm $day^{-1}$)

The potential evapotranspiration needs to be applied in accordance with the months during which rainfall occurs in order to determine actual evapotranspiration across the year. Alternatively, this can done by analysing chloride levels in the soil (Mazor et al., 1992), based on principles of chloride mass balance. It uses the ratio between the chloride concentration (mmol $l^{-1}$) in rainwater ($Cl_p^-$) and in ground-water ($Cl_{gw}^-$) to estimate what proportion of the water infiltrating the soil returns to the air via evapotranspiration:

$$E_T = \frac{Cl_{gw}^-}{Cl_p^-}(P - R)$$

These above formulas provide a method for calculating evapotranspiration, though in practice most regions of the world have evapotranspiration data available, and these should be used wherever they are available. In many arid climates, high temperatures and solar radiation mean that evapotranspiration is a very significant component of the water balance equation, and it is therefore very important to account for this in calculations. By way of illustration, Borst & de Haas (2006:74) estimate that in the Kitui region of Kenya, only 0.25% of water infiltrating the ground in the whole catchment area ends up reaching the river through lateral base flow, and that 99.75% is lost through evapotranspiration and groundwater recharge.

## 3.7 RAINFALL

We now turn our attention to the most crucial supply factor for sand dams: rainfall. The volume of rainfall required to recharge the sand dam reservoir is defined as 'design rainfall' (FAO, 2007). We define it here as $V_S(eff)$, which is calculated in Section 4.1. It is a critical threshold that must be satisfied reliably each year, even during years of low rainfall, and also long into the future, having mitigated the impacts of climate change (Aerts et al., 2007; Hut et al., 2008). Arid climates are characterized by extreme storm events occurring within highly seasonal patterns of rainfall (Maddrell & Neal, 2012:5). In its review of the impact of rainfall on small dams, the FAO (2001:17-18) distinguishes annual rainfall characteristics on the basis of its quantity and distribution during the year, and its variability year on year. Forzieri et al. (2008) build on this classification in order to investigate sand dam suitability in terms of rainfall. By using annual precipitation, $h_i$, for years $i = 1,2, \dots$ (assuming a single rainy season a year) they calculate the probability, $P(full)$, that the rainy season is able to fill the required storage volume, $V_S(eff)$, which requires a minimum threshold height of precipitation, $h$, such that:

$$P(full) = P(h_i \geq h)$$

$$h = \frac{V_s(eff) + E_T + G_c}{A}$$

The value $h$ is calculated based on the water balance equations in Section 3.1. Using 80 years of precipitation data in Mali, Forzieri et al. calculate $P(full)$ for $n$ potential sites and select only those which are ranked above the mean probability value:

$$P(full) \geq \bar{P} = \frac{1}{n}\sum_{i=1}^{i=n} P_i(full)$$

This is applicable only in regions of the world where rainfall is very low, providing a mid/catchment-level tool to identify favourable sand dam locations based on whether the catchment area of appropriate size and characteristics to ensure rainfall will recharge the sand dam. Forzieri et al. (2008) apply their model to Kidal, northern Mali, where there is a short, single rainy season with annual mean precipitation of only 129mm (ibid.:77). In such contexts it is indeed highly pertinent to establish whether precipitation is reliable enough and sufficient enough to warrant sand dam construction.

By contrast, areas where rainfall is abundant need not prioritise this parameter in the same way, but rather merely should ensure that rainfall will be sufficient with a 95% confidence interval (i.e. only once in twenty years will the sand dam reservoir fail to fill. This is elucidated by Borst and de Haas (2006), whose findings in Kitui, Kenya (mean rainfall 920mm per annum) curb its importance:

> *"The effectivity of the sand storage dams is less sensitive to the amount of rainfall. Even when there is much less rainfall, the amount of stored water remains the same. Only when the amount of rainfall drops below a certain threshold the amount of abstractable water will decrease. This threshold is dependent on the properties of the catchment. For the Kindu catchment decreased water availability due to insufficient rainfall will only occur when the annual rainfall drops below about 20 mm per year."* (ibid:84)

Rainfall and discharge data on a macro/regional level will govern the extent to which this is a critical factor in determining sand dam siting on a mid/catchment level. This accounts for the substantial variance in the literature regarding minimum rainfall threshold. Some research (FAO, 2001; Forzieri et al., 2008) is conducted in extremely arid contexts where rainfall volume struggles to meet the threshold of merely filling a reservoir each rainy season. Much other research (e.g. Borst & de Haas, 2006; Hussey, 2007; Maddrell & Neal, 2012) supposes levels of precipitation which render the issue mute, with most reporting that a mere 1-3% of river discharge is retained by the sand dam. This variance is witnessed in Table 5, showing the impact of various rainwater harvesting technologies on annual river discharge in different parts of the world.

*Table 5: Percentages of river discharge retained by rain harvesting in literature*

| Percentage | Country | Literature Source |
|---|---|---|
| 1.8 – 3% | Kenya | Aerts et al., 2007 |
| 2% | Kenya | Hut et al., 2008 |

| | | |
|---|---|---|
| 1% | Ethiopia | Lasage et al., 2011 |
| 1 – 3% | Ethiopia | IRC, 2014 |
| 11% | India | Bouma et al., 2011 |
| 64% | Australia | Schreider et al., 2002 |
| 50% | India | Garg et al., 2012 |
| 18% | Global | Wisser et al., 2010 |

Thus a bifurcation in the decision-making framework arises, whereby the extent to the water supply criteria is of importance in determining sand dam suitability and site selection depends on overarching rainfall characteristics at the macro/regional level:

- **Scenario A**: rainfall is fairly abundant, so the criteria is will be easily satisfied in almost all cases – in these cases the river witnesses flow reliably every year during rainy season;
- **Scenario B**: rainfall is scarce; the criteria is a critical factor which needs to be prioritized in decision-making; the size of catchment for each sand dam site should be considered such that there is high probability for sufficient water supply to recharge the storage reservoir.

## 3.8 ENVIRONMENTAL IMPACT

Environmental impact should be considered locally to assess the extent to which retention of water volume behind the sand dam affects the environs (Hussey, 2007:45). This is all the more pertinent in light of the impact of climate change and desertification. Future rainfall data and water resource usage should be forecast, looking at long-term rainfall trends. By way of example, Aerts et al. (2007) predicted that the percentage of river discharge retained by the existing 500 sand dams in the Kitui region of Kenya during the April-October season will increase from 3% in 1950 to 20% in 2100, which would likely result in downstream water shortages (ibid.:578). This issue is compounded should wider sand dam construction occur, forecasting that 1,500 sand dams would render a 60% total retention of river discharge in sand dam storage.

The most comprehensive analysis for the environmental impact river discharge reduction from sand dams was undertaken by Lasage et al. (2013). They looked at the impact of up-scaling sand dam construction in Ethiopia by drawing extensively from global research into the impact of rainwater harvesting on river discharges. The study concludes that for Ethiopia and other similar arid contexts, sand dams give extensive benefit when up-scaled, even at the expense river discharge reduction downstream, so long as the ‘environmental flow’ threshold is not triggered (ibid.). The environmental flow represents a threshold degree in discharge variation above which downstream water uses and natural processes can no longer be sustained (Smakhtin & Weragala, 2005:9). It is defined, in arid contexts (those for which sand dams are applicable), as one standard deviation below mean annual discharge.

$$mean - 1\,SD \ \leq parameter$$

This parameter is here applied to discharge, but we need to consider how it correlates to rainfall in order to undertake a statistical analysis based on rainfall data which is more readily available. Section 3.5 tells us that baseflow can be ignored (i.e. $Q_{in} = R$), and also that runoff, $R$, can be considered proportional to precipitation, $P$.

$$Q_{in} = \kappa P + c$$

Using this we can estimate the mean and standard deviation for river discharge by considering rainfall data instead. Thus the condition can be adapted:

$$\sqrt{\left|\frac{\sum(P_i - \bar{P})}{n}\right|} \ \geq h \quad where\ \bar{P} = \frac{1}{n}\sum_{i=1}^{i=n} P_i$$

This means that the amount of rainfall required to fill the sand dam ($h$), which will therefore not be available to flow down the river as it would have done naturally, must be less than a threshold level of fluctuation which might have happened anyway based on year by year rainfall variability. The FAO (2007) provides some helpful commentary to illustrate this practically:

> *"In temperate climates, the standard deviation of annual rainfall is about 10-20 percent and in 13 years out of 20, annual amounts are between 75 and 125 percent of the mean. In arid and semi-arid climates the ratio of maximum to minimum annual amounts is much greater and the annual rainfall distribution becomes increasingly skewed with increasing aridity. With mean annual rainfalls of 200-300 mm the rainfall in 19 years out of 20 typically ranges from 40 to 200 percent of the mean and for 100 mm/year, 30 to 350 percent of the mean. At more arid locations it is not uncommon to experience several consecutive years with no rainfall." (FAO, 2007)*

This sets a context for what might be considered a resilience ratio: areas which experience greater natural annual variation in rainfall are better equipped to handle the impact of a sand dam reducing total river discharge by a certain factor.

## 3.9 FEASIBILITY FRAMEWORK: WATER SUPPLY

This concludes the technical analysis for storage capacity, which is encapsulated in the feasibility framework in Figure 15Figure 22, with 2 key parameters: **Impermeable Bedrock** and **Appropriate Rainfall**.

*Figure 15: Feasibility framework for water supply*

**1. WATER SUPPLY**

**1A IMPERMEABLE BEDROCK**

i. Is the **geology appropriate**?

- If clay/mudstone/gneiss — YES → 1A satisfied
- if gravel/sand/silt/limestone: — NO → 1A not satisfied
- if sandstone/granite/trachyte: — → need to answer ii.

ii. Is the riverbed without any faults of fractures underneath it?

OR

are there scoop holes (with water) at the site in dry season?

- YES → 1A satisfied
- NO → 1A not satisfied

**1B APPROPRIATE RAINFALL**

i. Does rainfall suffice for SD to be filled (with 95% confidence)?

$$P(full) = P(h_i \geq h) \geq 0.95 \quad where \quad h = \frac{V_s(eff) + E_T + G_c}{A}$$

ii. Is the environmental impact tolerable, i.e. within natural variation?

$$\sqrt{\left|\frac{\sum(P_i - \bar{P})}{n}\right|} \geq h \quad where \quad \bar{P} = \frac{1}{n}\sum_{i=1}^{i=n} P_i$$

- IF BOTH YES → 1B satisfied
- OTHERWISE → 1B not satisfied

# 4. STORAGE CAPACITY

Criteria 2: maximal and suitable water storage capacity available in the sand dam reservoir.

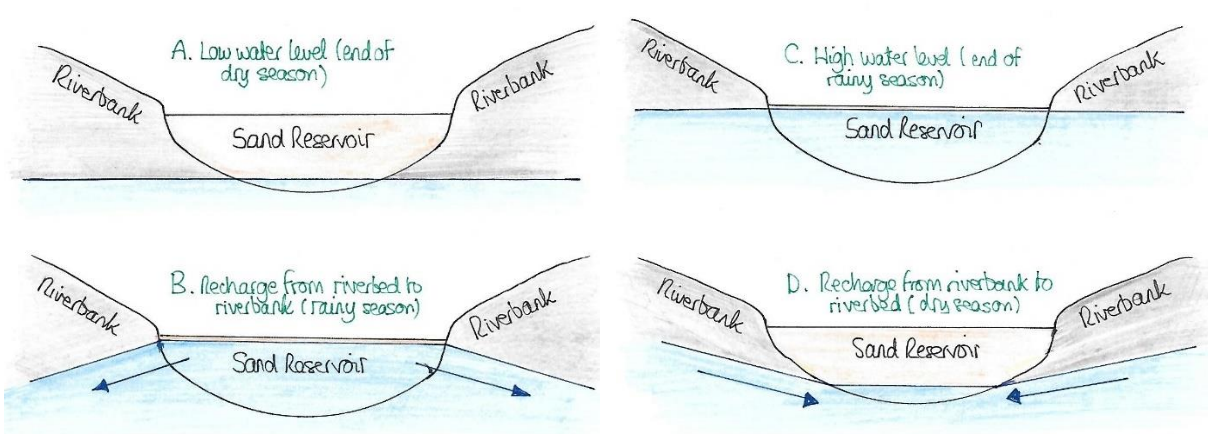
Chapter 3 determined conditions governing input and output from sand reservoirs – to ensure sufficient water supply and minimal water loss. This brings us on to the next criteria: the need for suitable water storage capacity in the sand reservoir itself. For sand dams to be viable they need to store a sufficient volume of water behind the sand dam. This concerns two main parameters:

1. Volume of the sand reservoir
2. Sediment particle size and transport characteristics

## 4.1. VOLUME OF THE SAND RESERVOIR

Water storage behind sand dams occurs in two different locations: the sand reservoir itself and the river banks. Primarily water is stored in the sand reservoir itself, which is our main purview here. However, significant water storage can also occur in the riverbanks bordering the sand reservoir, as illustrated in Figure 16 below:

*Figure 16: The effect of river banks as a secondary storage region for sand dams*




*[Adapted from: Borst & de Haas, 2006:83]*

Water storage in the riverbanks account on average for an additional 40% of storage capacity (Borst & de Haas), which is highly significant. However, it is very difficult to estimate this storage capacity for each context separately, since it depends on a number of different variables: rate of lateral baseflow, porosity of the banks, slope of underlying bedrock, extent of vegetation etc. (Gijsbertsen, 2007:8). Thus drawing from the example of Forzieri et al. (2008:82), this secondary storage factor is not considered in depth. Rather it is acknowledged as a potential enhancing factor for the water volume, and it is assumed that it increases the storage capacity by 40%.

The volume of water stored is determined by first calculating the volume of the sand. Later on we will consider how efficient this sand is at storing water (sediment particle size) and how likely it is that sand accumulation will occur (sediment transport). However, the potential volume of the sand reservoir needs to be considered first of all. There are a number of different proposed estimates for calculating the total volume of sand, $V_s$. The most commonly used is that put forward by Borst & de Haas (2006) and later by Maddrell and Neal (2012:13).

$$V_s = \frac{D \times W \times L}{4}$$

Where:

$D$ – Maximum depth of sand (m) from crest of spillway to deepest probe.
$W$ – Maximum width of sand once full of sand (m)
$L$ – Throwback (m) – i.e. length of the sand aquifer upstream = $D$ x 100 / slope of river bed (%)

The factor ¼ is a constant chosen to reflect the shape of the valley and the slope of the riverbed. It is important to incorporate the impact of evaporation (Section 3.3). Instead of $D$ we will choose instead the depth of sand which is not subject to evaporation, which we shall term $D_{true}$, calculated by considering the findings in Section 3.3:

$$D_{true} = D - h_{sand} \quad where \quad h_{sand} = 0.6 - \frac{0.1025}{n}$$

We are able to calculate a value for $V_S(eff)$ which is used in Section 3.7 with respect to rainfall. We use this new value $D_{true}$, we incorporate porosity, $n$, and add 40% to factor in riverbank storage:

$$V_S(eff) = V_s.n$$

$$V_S(eff) = 1.4\frac{n}{4}(D - 0.6 + \frac{0.1025}{n}) \times W \times L$$

There are other formulations put forward in the literature (e.g. Gezahegne, 1986) proposing more complex and potentially accurate measures, but these would only be required where the morphology of the riverbed and banks is so complex that it requires a more in depth analysis. In such cases, more extensive probing of the sand reservoir and mapping of the topography would be necessary. Either way, for a location to be suitable this volume should be as large as possible and large enough to meet the purpose for which it was designed.

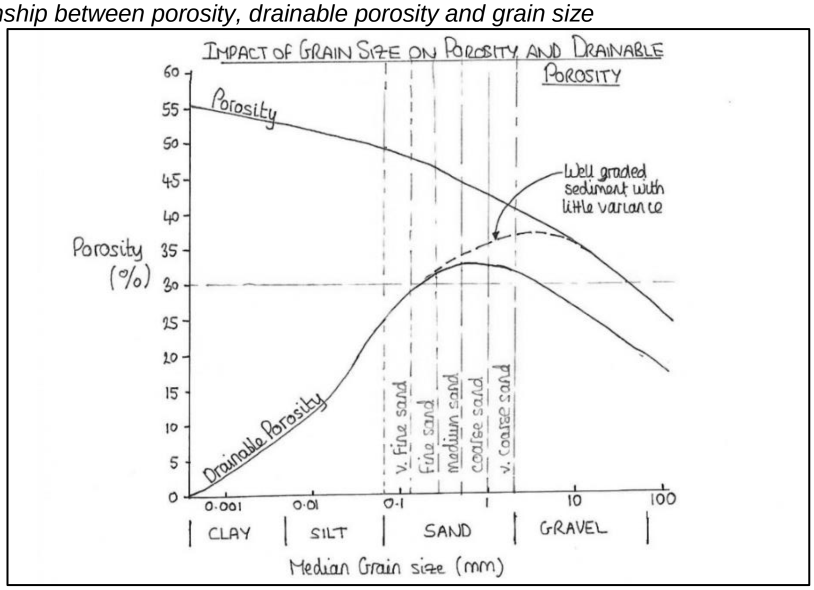
## 4.2. SEDIMENT PARTICLE SIZE

Sand dams rely on the natural build-up of sediment behind the dam to store water. The particle size of this sediment considerably impacts the amount of water that can be abstracted. In the literature base – both practitioner approach and analytical approach –there is broad consensus regarding its importance; most sources cover this topic at some depth. Maddrell & Neal summarize in this way:

> *"The ideal sediment has a high sand content (especially coarse to medium sands) and little or no silt and clay content. The higher the percentage of coarse sand and the more uniform the sediment is, the greater storage and abstraction potential from the dam." Maddrell & Neal (2012:10)*

This point is illustrated succinctly in Figure 17 below.

*Figure 17: Relationship between porosity, drainable porosity and grain size*




*[Adapted from: Maddrell & Neal (2012:10)]*

This graph highlights the critical distinction between porosity and drainable porosity. The porosity is a measure of how much water it takes to saturate a given volume of the material, expressed as a percentage (Hussey, 2007:15) The drainable porosity (otherwise known as the specific yield**)** defines the amount of water that can will drain from a saturated volume of the material under normal gravity (ibid.). Drainage porosity is of particular relevance to sand dams, since it is this parameter which determines how much water is available per cubic metre of storage capacity. Nissen-Petersen (2006:2) express this same principle quantitatively in Table 6:

*Table 6: Drainage porosity for a range of sediment grain sizes*

| | Silt | Fine Sand | Medium Sand | Coarse Sand |
|---|---|---|---|---|
| Size (mm) | <0.2 | 0.2 to 0.5 | 0.5 to 1 | >1 |
| Water Extraction (Drainage Porosity) | 5% | 19% | 25% | 35% |

*[Adapted from: Nissen Petersen, 2006:2]*

It can thus be seen that medium to coarse sand is the most appropriate for the sand reservoir, with an optimum abstractable yield of 35% for coarse sands. This is very widely accepted in literature (Borst & de Haas, 2006; Fewster, 1999; Gezahegne, 1986, Gijsbertsen, 2007; Munyao et al., 2004; Maddrell & Neal, 2012; Nissen-Petersen, 2006; RAIN, 2007; Stern & Stern, 2011, among others).

Furthermore, the dotted line in Figure 17 above illustrates the importance of uniformity of grain size. This is to avoid siltation whereby smaller particles would clog up the porous coarse sands (similar to capping in Section 3.5). Indeed there are a number of case studies in literature which cite a failure (a) to ensure adequate sediment size and (b) to ensure uniformity, for the non-functioning of sand dams post-construction; Gijsbertsen considers the Ana catchment in Kitui:

> *"Most dams in this catchment are totally filled, but several scoop-holes behind of the dams show that the sediment is not only coarse sand. The first ~60 cm of the riverbed behind the dam consist of a coarse sand layer... The next layer up to the bedrock consists of a low permeable silt/clay layer. This means that water will infiltrate in the upper ~60 cm, but infiltration will cease at the low permeable layer. The total storage of the sand dam is therefore assumed to be much lower than originally expected."* (Gijsbertsen, 2007:22).

Thus sand dams rely upon the build-up of sandy sediment, which should be defined as having a minimum grain size of 0.2mm (Nissen-Petersen, 2006:2).

## 4.3. SEDIMENT TRANSPORT

Having established the importance that coarse sands be present, we must now turn our attention to the physical processes which lead to the accumulation of these coarse sands behind the dam structure. Sand dams are only suitable in locations where there is a high level of confidence that this will indeed occur, and this is to a large extent determined by sediment transport characteristics of the river and related catchment area. In simple terms, the conditions need to ensure that coarse sands are transported in the river flow such that they can end up deposited behind the sand dam.

Maddrell and Neal explain that a high rate of sediment transport is essential and explain in this way:

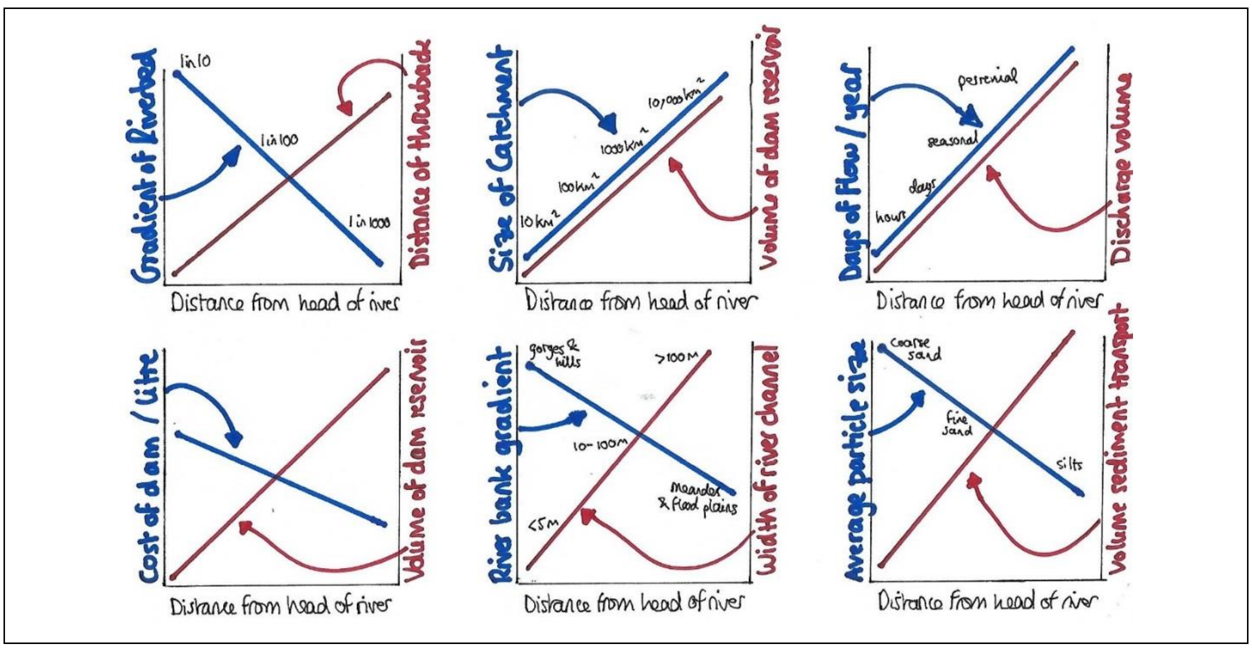
> *"Rate of sediment transport is determined by how long and fast seasonal rivers flow for throughout the year. This is determined by how much overland flow there is and how much sediment is suspended in this flow. This is determined by many inter-related factors such as climate, topography, vegetation, soils, geology and land use."* (Maddrell & Neal, 2012:16)

There are a wide range of such factors at the catchment level which impact sand dam feasibility. Using a practitioner approach, Maddrell and Neal (ibid.:18) look at these interconnected factors to establish correlations between them as follows:

- Rivers with larger catchment areas flow for a greater proportion of the year with deeper and wider channels in order to handle the greater volume of flow discharge.
- Peak rainfall intensity decreases as the catchment size increases because it is averaged across the whole area, and thus flows are less torrential.
- Conversely, the smaller a catchment is, the steeper the slope of the riverbed will be, which results in greater velocity of flow.
- A steeper catchment slope means greater runoff, higher rates of erosion and sediment load. Furthermore, a steep slope causes floods rise and fall more quickly.
- However, velocity is determined not just slope, but also by discharge and riverbed friction. In actual fact, as catchment size increases, friction drops and rivers become more hydraulically efficient. There is not always a straightforward relationship between catchment size and velocity.
- Higher flow velocities mean greater sediment transport, and also a greater grain size able to be transported by the flow. (ibid:18).

These river characteristics can be summarised in the following graphs outlining the relationship between 'distance from head of river' (related to catchment size by channel sinuosity):

*Figure 18: How distance from head of river relates to other variables*




*[Adapted from: Maddrell & Neal, 2012:16]*

Though the above empirical findings provide a useful basis for understanding sediment transport, it is important to conduct a more rigorous mathematical analysis. This is provided for by considering the Shield's parameter, which provides a relationship between sediment transport and flow velocity.

Zhou Liu's research (1998) provides a thorough investigation of this, and Gijsbertsen (2007:19-21) then applies this to the context of sand dams:

Critical Friction Velocity, $u_{*c}$ (in ms$^{-1}$) is the threshold velocity for which a stationary grain starts to move. This is determined with the following equation:

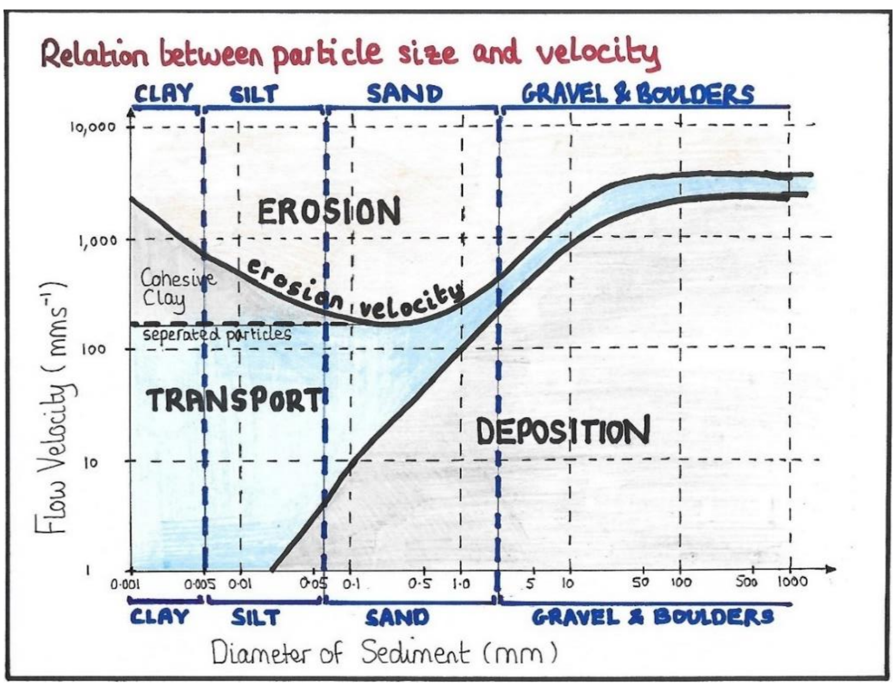
$$u_{*c} = \sqrt{\theta_c (s-1) g d}$$

Where $d$ is the grain diameter (m), $g$ is the gravitational constant (approx. 9.8 ms$^{-2}$), $s$ is particle fluid density ratio (%), otherwise known as specific gravity. $\theta_c$ is the critical Shield's parameter, which is calculated using the Shield's diagram by inputting the 'sediment fluid parameter' $S_*$, which is calculated in the following way:

$$S_* = \frac{d\sqrt{(s-1)gd}}{4v}$$

Where $v$ is the kinematic viscosity (m$^2$s$^{-1}$) which is approximately 10$^{-6}$ at 20$^{o}$C. Thus we are able to calculate the threshold at which sediment is transported in the river for different grain sizes, a summary of which is presented in Figure 19:

*Figure 19: Impact of flow velocity and particle size on sediment transport*




*[Adapted from: Borst and de Haas, 2006:56]*

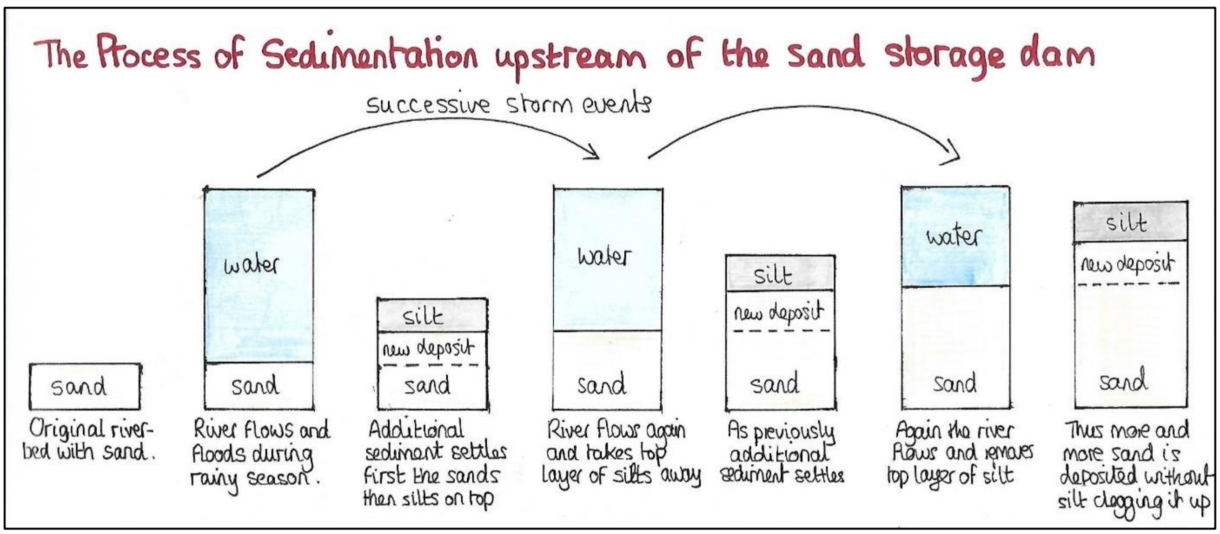
Above it was established that the minimum acceptable grain size for sand dam reservoirs is 0.2mm, which calculated graphically from Figure 19, yields the following value for critical friction velocity:

$$u_{*c} = 0.2 \text{ ms}^{-1}$$

In practical terms, this represents the minimum flow at which sand (of grain size minimum 0.2mm) will be transported in the flow. For sand dams to accumulate this threshold minimum grade of sand, the flow of the river must be above this minimum velocity. It is worth noting that this value assumes open flow without the friction of riverbanks, so in practice a higher mean value will be required across the whole cross-section of the river's flow. Furthermore, with large grain sizes this will increase (e.g. the flow should be 1 $ms^{-1}$ to transport gravel of 5mm).

In Hydrological terms, prior to the sand dam reaching 'maturity' (when the sand accumulation is complete), the dam acts to slow down flow velocity behind the dam such that the sand being transported is deposited, whilst the suspended clays and silts pass over the spillway in the discharge. This enables only the coarse sand to be selected for and sand reservoir. Figure 20 provides a helpful illustration of the way this accumulation of sand occurs.

*Figure 20: The gradual build-up of coarse sands as a result of storm events*




*[Adapted from: Borst & de Haas, 2006]*

However, even where the river ensures sediment transport above the critical friction velocity threshold, the hydrology of the dam can still cause an overly dramatic drop in flow velocity such that silts (and even clays) are be deposited alongside sands, resulting in the undesirable clogging up the sand reservoir and a resultant lower specific yield. This typically occurs either where the dam obstructs the flow too substantially as a result of being too high, or relatedly the region does not experience sufficient 'storm events' in its rainfall to ensure that the flow is torrential enough to breach the dam through the spillway (Nilsson, 1984).

Rather than making this an issue of feasibility, it can be addressed by appropriate design planning (c.f. Leakage issues in Section 3.4). This is outlined by Ertsen and Hut (2009:16-17). They advocate a longer time-frame for construction, whereby the dam height is increased incrementally after each rainy season. This is typically undertaken in 30cm increments (Nissen-Petersen, 2006). Though it does increase cost and causes difficulty in mobilizing the workforce over successive years, it is justifiable as it ensures a high quality sand reservoir. This is corroborated by Gezahegne (1986:31) who explains the rationale for such a construction approach:

> *"The basic idea is to limit the height of each stage in order to keep a sufficiently high water velocity, so that fine particles are washed out from the reservoir while the coarse particles settle. The height of each stage is determined by estimation of the sedimentation process in the reservoir [through] calculations of water velocities."* (Gezahegne, 1986:31)

Here no attempt is made to outline fully design considerations, which is beyond the scope of this research. It is sufficient to note that the criteria demands a sufficiently high flow velocity to guarantee the transport of the necessary grade of sands.

## 4.4. SEDIMENT INDICATORS

Thus we have established a two critical parameters for sediments at sand dams:

(1) Coarse and medium sands (grains of minimum diameter 0.2mm) are necessary in the sand dam reservoirs; and clay/silt must be minimally present.

(2) Sufficient flow velocity (minimum 0.2 $ms^{-1}$) is required for transport and accumulation of sand behind the dam.

It is now necessary to consider how these parameters can be assessed practically for sand dams. There are a number of indicators which can be derived and used for this purpose, which are corroborated by case studies and practitioners.

First most obvious is the presence of suitable sand in the riverbed. If the river has suitable sand in its riverbed, then these same morphological and flow characteristics which caused this will still govern sediment transport after sand dam construction. This is elaborated by Gijsbertsen:

> *"When coarse material is available in the riverbed, the bed itself gives an indication that the surrounding area is (geo)morphologically suitable of generation and deposition of coarse sediments. When the coarse sediments are not available in the riverbed the chance of deposition of unfavourable sediments behind a dam becomes larger … When there is no sand available in the riverbed the conditions in the catchment area do not meet the criteria for constructing sand dams."* (Gijsbertsen, 2017:27-28)

This is the best means of determining suitable sediment properties for sand dams.

However, this indicator should not be overly relied upon, or considered in exclusion to other factors. Many case studies (Hussey, 2007; Gezahegne 1986; Fester, 1999; Stern & Stern, 2011; Nilsson, 1984) have reported the successful build-up of sand behind the dam even when sited on sections of rivers and streams where the bed where there has previously been limited or no sand deposits. Thus even where locations do not have natural build-up of sands, there can be other indicators which lead to confidence that this will occur when a sand dam is constructed. Gezahegne appeals to this point in stating that “one should not be immediately discouraged if there are no sand deposits along the river, when surveying an area to find suitable site for sand-storage dams. This might be the result of a high-intensity rainfall pattern causing such heavy flows that deposition is not possible under natural conditions.” Here we see that though coarse sands may exist, and though sediment transport may occur, the rate of flow is such that the deposition threshold is not met.

In such scenarios, it is necessary to look at two factors:

(a) Whether the erosion and transport of sediment occurring in the catchment area will result in coarse sediments being available at the sand dam location;
(b) Whether the flow of the river is such that the absence of these sediments can be naturally attributed to the high velocity of flow.

Both of these are strongly correlated to slope characteristics, which in turn is related to the size of the catchment area as illustrated above in Figure 18.

Regarding (a), Gijsbertsen (2007:2) undertakes a statistical comparison between catchment slopes and sand in rivers and concludes: that “Catchment areas with an average slope smaller or equal to approximately 2° show large similarity with non-sandy riverbeds. Runoff generated in these catchment areas appears to be too low for transport of coarse grained material.” Thus, for our purposes we consider that where sand is not present at the proposed site, a mean slope catchment of at least 2% assures us that sufficient erosion will be occurring to ensure the availability of coarse sediments.

Regarding (b), most practitioners refer to riverbed gradient and catchment slopes in their evaluation of sand dam feasibility, though few undertake the analysis above which underpins its pertinence. Furthermore, there is significant disagreement regarding what the appropriate ranges of slopes of rivers for sand dams should be: 0.4% (Borst & de Haas, 2006), 1.5 - 4% (Gezahegne, 1986), >2% (Gijsbertsen, 2007), <1% (Hussey, 2007); 0.125 - 15% (Fewster, 1999), 0.2-5% (Maddrell & Neal, 2012), 2-4% (RAIN, 2007).

These differences can be attributed to the aforementioned dichotomy between analysts and practitioners, whereby the rationale for the different recommended slopes is motivated by different starting points. The analysts look at the problem theoretically and therefore are required to put forward a threshold to guarantee sediment transport, and thus it will typically require an overestimate in order to establish not just 'necessity' but also 'sufficiency'. By contrast, practitioners typically gather data empirically by looking at existing case studies, and as such will witness effective sediment accumulation at much lower slopes, occurring as a result of torrential flows, which analysts cannot rely upon for their calculations.

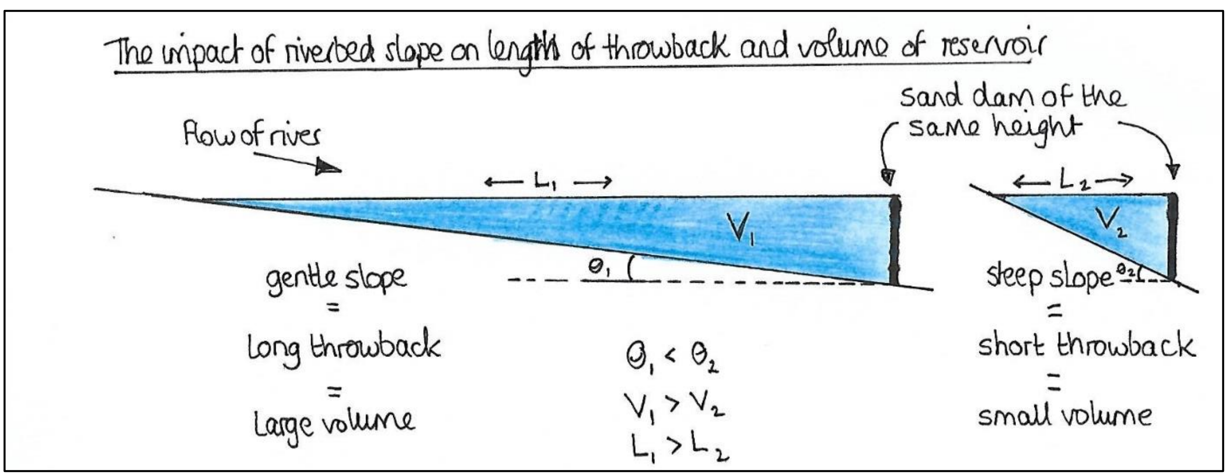
In order to have a high level of confidence that sand will accumulate, based on analysis of morphology and flow, a steeper slope is recommended Gezahegne sets forth a summary:

> "*The particle size of sediments accumulated along streams and in river beds is proportional to the topographical gradient, whereas the depth and the lateral extent of such deposits are inversely proportional to the gradient. The optimum relation between these two factors, and thus the most favourable sites for sand dams, is found on the gentle slopes in the transition zone between hills and plains.* "

Gezahegne (ibid.) concludes a necessary riverbed gradient of between 1 and 5% is required

Finally, it is worth noting that the impact of slope on the volume of water held behind the dam is significant and clearly demonstrated by Figure 21. Though this does not pertain directly to this parameter (regarding sediment size) it is nonetheless an important factor, which motivates us to discount all riverbed slopes in excess of 5% on account of inefficient water storage.

*Figure 21: The relationship between slope, throwback and water volume*




## 4.5. FEASIBILITY FRAMEWORK: STORAGE CAPACITY

This concludes the technical analysis for storage capacity, which is encapsulated in the feasibility framework in Figure 22, with 2 key parameters: **Reservoir Volume** and **Sediment Accumulation**.

*Figure 22: Feasibility framework for storage capacity*

**2. STORAGE CAPACITY**

| | |
|---|---|
| **2A RESERVOIR VOLUME** | |
| i. Is the reservoir volume sufficient for the purpose?<br>$V_S(eff) = 1.4\frac{n}{4}(D - 0.6 + \frac{0.1025}{n}) \times W \times L$ | YES → 2A satisfied<br>NO → 2A not satisfied |
| **2B SEDIMENT ACCUMULATION** | |
| i. Is sand (grain size >0.2mm) naturally present in riverbed? | YES → 2B satisfied<br>NO → need to answer ii. |
| ii. Does the catchment have a mean slope >2%?<br>AND<br>Does the riverbed have a slope of between 1% and 5%? | IF BOTH YES<br>→ 2B satisfied<br>OTHERWISE<br>→ 2B not satisfied |

# 5. AFFORDABILITY

<u>Criteria C:</u> The sand dam is affordable, both initially in construction & long-term in its sustainability.

Favourable water supply (Chapter 3) and storage characteristics (Chapter 0) are alone insufficient to determine feasibility. This chapter engages with the impact of additional technical factors on sand dam affordability and sustainability.

Affordability is a gauge of sand dam benefits as against its costs, and by definition cannot be considered in exclusion to other comparable solutions. Cost is always relative, since it depends on what other options exist, how effective they would be and how much they would cost. To undertake such an analysis generically is too complex and locally-specific, so it suffices to acknowledge that a cost-benefit analysis will be a necessary component of a full feasibility study, to compare sand dams against other viable options (Gezahegne, 1986:11; Stern & Stern, 2011:2; Maddrell & Neal, 2012:16).

Furthermore, cost-benefit analyses are difficult to undertake comprehensively, given that future benefits are often unknown and unquantifiable, and the whole cost (economic and otherwise) is hard to estimate accurately (Carruthers & Browne, 1977). Therefore, here we merely seek to introduce some tools which can be used either (a) to definitely exclude sand dams on the grounds of unaffordability, irrespective of other possible solutions, or (b) to offer a means of comparison between different prospective sand dams sites (on the mid/catchment level) by developing tools which give insight into affordability. The chapter will not determine whether, on grounds of affordability, sand dams provide the best cost-benefit ration; but rather will establish the likelihood that it might, by considering the following three parameters

## 5.1. CEMENT AVAILABILITY

The concept of 'cost' is multi-dimensional and is far broader than merely financial costs. However, typically financial cost is the most immediately measureable variable, and thus suitably acts as a primary indicator (Gezahegne, 1986:11). Many reports and papers make reference to the cost of cement being a good indicator of the financial cost of the whole sand dam (Maddrell & Neal, 2012:16; Munyao et al., 2004:14; Nissen-Petersen, 2006:26; RAIN, 2007:16; ). Furthermore, the burden of cement purchase is often the aspect of implementation which is covered by the outside agent, whether local government or an NGO (Ertsen & Hut, 2009:17). Though other types of groundwater dam have been successfully constructed without using cement, the literature provides broad consensus that in the case of sand dams cement is imperative. The perpendicular obstruction of the river channel – which is often subjected to torrential flows during storm events – requires a material strength which motivates the needs for cement construction (Gijsbertsen, 2007:18). Thus it is necessary to ensure that locally (i.e. at the nearest town or city) a reliable supply of cement is available at an equitable price. Without such availability, sand dam construction is unlikely to be possible, and it will certainly hinder any potential 'up-scaling' regionally to implement sand dams more widely.

Furthermore, once local materials and local labour are accounted for (Section 5.2), and thus omitted from the 'overhead' costings, cement represents by a long way the greatest remaining cost of sand dam construction. Within literature there is a range of percentages put forward for this: 70% (Stern & Stern, 2011:15); 75% (Munyao et al., 2004:21); 66% (Nissen-Petersen, 2006:26); 63-71% (Maddrell & Neal, 2012:46). Thus anything from two-thirds to three-quarters of the cost is attributed to the procurement of cement. As such much of the rest of this chapter will deal with the technical considerations which impact on the quantity of cement which is required in light of dam dimensions and local factors.

## 5.2. LOCAL LABOUR AND MATERIALS

Other costs (e.g. labour, local materials) are typically covered by the users themselves. Indeed this is encouraged as a means of promoting participation and ownership (Stern & Stern, 2011:16; Ertsen et al., 2005:3, Maddrell & Neal, 2012:45). It will typically represent 40% of the total cost of the sand dam (ibid.:46). Where local communities commit their own resources into a new technology they have a greater stake and incentive in ensuring it is maintained long-term (ibid.). This has two dimensions:

**Investment in the form of labour**: there needs to be a critical amount of households engaged in the sand dam project and willing to commit manpower to the task (Ertsen et al., 2005:3; Borst & de Haas, 2006:29). The literature considers a minimum to be between 20 and 40 households (Munyao et al., 2004:12; Gijsbertsen, 2007:19; Maddrell & Neal, 2012:34), who are each able to commit one adult member of the household to help throughout the construction timeframe. Typically larger communities than this will be more appropriate, both in order to reduce the construction burden per capita and also because in some cases sand dams have capacity to provide greater domestic water supply. However, at very least there should be a sufficient labour force.

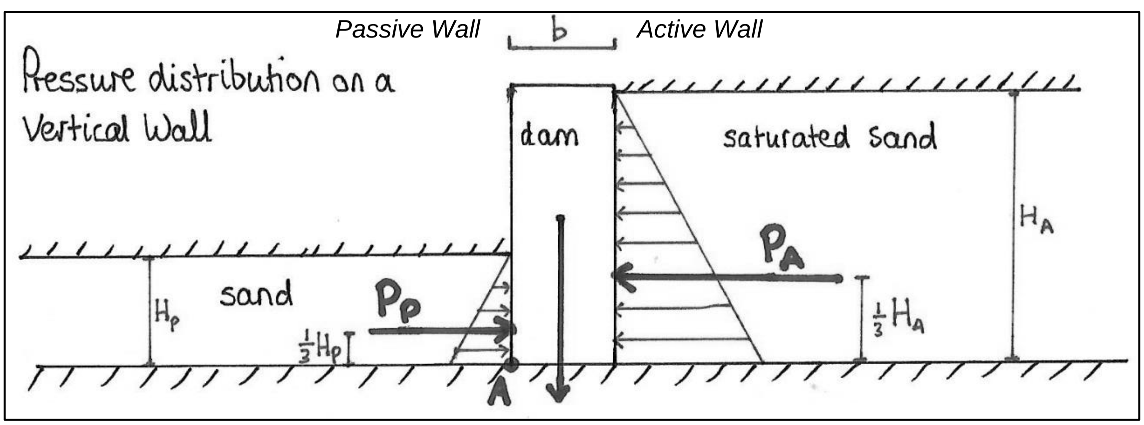
**Collecting and transporting materials available locally**: local materials must be easily available nearby, the most important materials being stones/rocks, sand and water. Where these are not locally available sand dam construction will not be feasible, since the costs of transporting these to the site render the whole prospect unaffordable (Gijsbertsen 2007:19; Munyao et al., 2004:12; RAIN, 2007:13).

## 5.3. ACCESSIBILITY OF BEDROCK

The bedrock beneath the riverbed must be easily accessible for the sand dam to be affordable, and this is for a number of reasons, the most important of which is the cost of excavation. The deeper the bedrock lies beneath the riverbed the more costly and time consuming it is to dig down, and it therefore becomes less affordable. Maddrell and Neal (2012:13) state that "due to the cost and labour required for excavation, sand dams are rarely built where the bedrock is more than three metres below the level of the existing streambed, unless it is for a narrow stretch of the riverbed." Borst and de Haas (2006:43) refer to case studies where after several metres of digging the impermeable layer has still not been reached, resulting in the sand dam being built without an impervious foundation, undermining its effectiveness as leakage volumes under the dam will be considerably higher.

A second factor is the higher cost of cement with deeper bedrock, both as a result of the greater cross-sectional area of river that must be covered, but most importantly as a result of the trapezoidal shape of the dam meaning that each extra metre of depth contributes to a required increase in the width of the dam. Gezahegne (1986) expands on this by considering dam dimensions in light of the forces at work in the dam, and the necessary shape of the dam to ensure long-term structural soundness. The main loads acting on sand dams are soil and hydraulic, and in the case of cement dams the dam wall needs to be of the right dimensions to carry those loads. The design needs to overcome overturning forces as well as sliding forces as a result of these loads (ibid.). A simplified diagram (with a square shape) is presented below:

*Figure 23: Pressure distribution on a vertical wall*




*[Adapted from: Gezahegne, 1986:9]*

We can thus derive from the pressure distribution, $P_A$ and $P_P$, and the horizontal forces, $F_A$ and $F_P$, on the active and passive walls respectively (ibid.):

$$P_A = K_A.\gamma_{S.S}.H_A \quad and \quad F_A = \frac{K_A.\gamma_{S.S}.{H_A}^2}{2} \quad where \quad K_A = \frac{1-\sin\varphi}{1+\sin\varphi}$$

$$P_P = K_P.\gamma_S.H_P \quad and \quad F_P = \frac{K_P.\gamma_S.{H_P}^2}{2} \quad where \quad K_P = \frac{1+\sin\varphi}{1-\sin\varphi}$$

Where:

$\gamma_{S.S}$ – Unit weight of saturated sand (KNm$^{-3}$)

$\gamma_S$ – Unit weight of sand (KNm$^{-3}$)

$H_A$ – Height of the sand on the active wall (m)

$H_P$ – Height of the sand on the passive wall (m)

$K_A$ – Coefficient of active soil pressure

$K_P$ – Coefficient of passive soil pressure

$\varphi$ – Angle of internal friction

The vertical force, $F_V$, as a result of the weight of the dam, can also be calculated as follows, where $\gamma_{wall}$ is the unit weight of the wall material (KNm$^{-3}$) and $A_{wall}$ is the area of the wall (m$^2$):

$$F_V = \gamma_{wall}.A_{wall}$$

We can use these formulas to establish the thresholds at which the dam is considered safe against overturning and sliding, by appealing to the following two theoretical formulae:

**<u>Safety against sliding</u>**: $F_S = \frac{F_V}{F_H}\tan\varphi \geq 1.5$ where $F_H$ is the sum of horizontal forces above.

As can be seen the minimum threshold is proportional to $F_V/F_H$. $F_H$ increases by a square factor (see formulas for $F_A$ and $F_P$ above) as the height disparity between the active and passive wall increases, as is the case with deeper bedrock. This must thus be matched by a corresponding increase in $F_V$, which only increases by a linear factor as the height increases (resulting from $A_{wall}$). Thus $\gamma_{wall}$ must be increased instead to meet the threshold, which necessitates a greater width of dam at greater expense.

**<u>Safety against overturning</u>**: $F_{O.S} = \frac{M_R}{M_O} \geq 1.5$

Where $M_O$ is the overturning moment of active earth pressure, and $M_R$ is the resisting passive moment at point A (in wall above), due to the weight of the wall. We can sum about A using the formulae above to calculate these moments, where b is the width of the dam (m):

$$M_O = \frac{1}{3}.P_A.H_A \qquad and \qquad M_R = \frac{1}{3}.P_P.H_P + \frac{1}{2}bF_V$$

In the case of sand dams, where the discharge flowing over the spillway often results in a very small value for $H_P$ as a result of erosion, the second factor ($\frac{1}{2}bF_V$) is the most important, and is directly proportional to the width, b, of the dam. Thus it can be seen that with $H_A$ increasing (in the case of deep bedrock), a corresponding increase in the width of the dam is required, at considerable additional cost. Thus, with the help of Gezahegne's (1986) calculations above we see the rationale for pursuing accessible bedrock for sand dams, since in addition to the reduced labour costs mentioned above, it means a less complex structure and a lot less cement required to ensure an appropriate width of dam.

The 'analysis' approach has yielded the above results, and is corroborated by practitioners, who are in broad agreement about the importance of having accessible bedrock for the construction of the dam. Al Taiee (2010:35) states that there should be "rock with impermeable layer at a depth of a few metres", and others provide more specific thresholds, with Maddrell and Neal (2012:13) recommending a maximum of 3 meters depth, Nilsson (1984) providing maximum limit of 3-6 metres, and Borst & de Haas (2006:43) setting the threshold at 4 metres. Here we have established a clear parameter for meeting this criteria, with the need for shallow bedrock (maximum 3 metres) required for sand dams to be suitable. This criteria can be evaluated on a macro/regional or mid/catchment level by looking at geological trends, but more importantly at the micro/siting level, with the use of probing rods.

## 5.4. WIDTH OF RIVER

We have explored the impact of cement costs on decisions about depth of the sand dam, and now it is appropriate for us to consider how it affects decisions about the width of sand dams. The first aspect to note here is that though larger sand dams cost more in gross terms, they are also typically more efficient, yielding a greater volume of water per dollar of investment. This is appositely shown by Maddrell & Neal (2012:16-17), who observe 'large dams on large rivers are more cost effective.' They illustrate with Table 7 comparing three different dam sizes. It can be seen that the second dam is 3 times more expensive (in cement terms) but stores 30 times more water volume.

*Table 7: Comparison of the storage capacity for different sizes of dam*

| | **Width** | **Depth** | **Throwback** | **Porosity** | **Storage** | **Stream length** | **Riverbed slope** | **Bags of cement** |
|---|---|---|---|---|---|---|---|---|
| **Dam 1** | 3 m | 2 m | 296 m | 40 % | 178 $m^3$ | 2 km | 1/74 | 248 |
| **Dam 2** | 30 m | 3 m | 706 m | 40 % | 6,353$m^3$ | 24 km | 1/118 | 811 |
| **Dam 3** | 50 m | 6 m | 2,259 m | 40 % | 67,765$m^3$ | 40 km | 1/188 | Unknown |

*[Adapted from: Maddrell & Neal, 2012:16]*

Thus we should be clear that this affordability criteria is not seeking the smallest capital expenditure on a sand dam, but rather cost effectiveness, with maximal benefit (and specifically volume of extractable water) for minimal cost.

Furthermore, it is noteworthy that most practitioners state a 'maximum width' for sand dams, whereby locations with river width above this threshold are not considered suitable. Gijsbertsen (2007:17) places this threshold at 25 metres, as do (Nissen-Petersen, 2006) and RAIN (2007:8). Maddrell and Neal (2012:4) propose a range of 10-30 metres in width. Though there is no 'hard and fast' rule about this, as indicated by Stern & Stern (2011:1) who claim that sand dams can be built up to a width of 90 metres, there are a number of reasons for preferring a smaller width. Firstly, sand dams aim to be an 'appropriate technology' specifically intended for rural contexts in the developing world, making use of local labour and local materials. Thus keeping the construction 'small-scale' is preferable since it is can be more easily undertaken and maintained without external support or expertise (Schumacher, 1973). Secondarily, similarly to considering greater depths of dam, as the river width is increased so does the complexity of the construction, with higher river discharges requiring more complex engineering to ensure its feasibility, which is often incongruent to the context. Finally, greater capital expenditure means higher risk and more at stake if the sand dam does not function as hoped, or if it is damaged or destroyed by storm events. As such this paper upholds the advice of practitioners and recommends that on principle sand dams should be constructed only where the river width at the proposed site is less than 25 metres.

## 5.5. NATURAL NARROWING

Sand dams are appropriate in locations where the natural morphology and rock formations mean that a small dam results in a very large reservoir of sand behind it, thus producing an excellent cost-benefit ratio. This occurs when there is a natural narrowing of the river: "where rainwater from a large catchment area flows through a narrow passage" (Al-Taiee, 2010:35). A relatively small dam would yield a (proportionally) significant volume of extractable water. Borst and de Haas (2006:30) explain this phenomenon similarly, focusing on what they call a 'rock outcrop':

> *"A location in the river with a natural rock outcrop is preferred to build a dam. The outcrop forms a natural barrier, behind which water and sand already accumulate. If the dam is built on top of the outcrop, it doesn't have to be as large as it would be in case it would be built on a deeper part, which means less effort and costs."*

This concept is discussed widely in the literature base (e.g. ibid., Gijsbertsen 2007:17-19, RAIN, 2007:8-10, etc.) but the most thorough and analytical handling of it is undertaken by Forzieri et al. (2008:78-81). They actually consider this 'natural narrowing' of a watercourse to be the primary criteria by which to screen for potential sand dam sites. The main reason for this is that the reduction in sand dam dimensions and the associated cost saving is the most important determinant for selecting or discounting a particular location (Nilsson, 1985).

Forzieri et al. (2008) undertook this analysis of ‘narrowing’ using satellite data to undertake large-scale surveys, but it can equally be undertaken on the ground by using local knowledge and tracking riverbeds which are close to population centres. Indeed, this condition can be used as a rudimentary means of selecting prospective sand dam sites to be used in the feasibility study (Section 6.4). It provides data from a range of sites which we can be inputted into other feasibility parameters. Furthermore, this parameter can be used to rank sand dam sites to establish where best, within a given catchment or stretch of riverbed, the sand dams should be located.

A method is introduced by Forzieri et al. (ibid.) to measure the ‘quality of the narrows’, which is the ratio between the volume of the dam structure and the volume of water stored in the sand reservoir. The volume of the dam, $V$ ($m^3$) is estimated by assuming a triangular shape of dam (c.f. a square approximation in Section 5.3):

$$V_{dam} = \frac{W.h.s}{2}$$

Where $W_{dam}$ is the width (m), $h$ is the height (m) and $s$ is the base thickness (m) of the dam. However, it can be assumed that the base is approximately 1/40$^{th}$ of the width of the dam *(ibid.) which yields the following calculation for the dam’s volume:

$$V_{dam} = \frac{W_{dam}.h.s}{2} = \frac{W_{dam}.h.\frac{W_{dam}}{40}}{2} = \frac{{W_{dam}}^2.h}{80}$$

The volume of the water behind the dam, $V_s(eff)$, was calculated previously in Section 4.1. When considered in ratio with the volume of the cam, we are able to calculate $\alpha$, the ‘quality of the narrows’ coefficient:

$$\alpha = \frac{V_s(eff)}{V_{dam}} = \frac{1.4\frac{n}{4}(D - 0.6 + \frac{0.1025}{n})W \times L}{\frac{h}{80}{W_{dam}}^2}$$

$$\alpha = 28\frac{n.W.L}{h.{W_{dam}}^2}(D - 0.6 + \frac{0.1025}{n})$$

This coefficient is considered to be “in each site the ratio between benefits and costs associated at realisation of the barrage. The benefits are constituted by live storage volume; the costs are constituted by structure volume” (Forzieri et al. 2008:82). This parameter is clearly oversimplified, and this is openly acknowledged by its proponents (ibid.). However, it does provide essential guidance for comparing a range of different prospective sites and evaluating which ones would be most viable. Furthermore, it can be possible for use this coefficient in comparison with other prospective technologies and the economic capacity of the users to establish whether the sand dam option would be viable.

Here it sufficient to note that (a) on a micro/siting level, the narrowest points of the river, and those coinciding with rocky outcrops, are those considered most suitable for sand dams, and (b) this 'quality of the narrows' analysis can be undertaken to provide a tool of comparison between different sites, and also averaged at a regional level to determine the whole region's cost-effectiveness quotient in comparison to other regions.

## 5.6. WILLINGNESS TO PAY

The final major factor in considering sand dam feasibility is the community itself, and their 'willingness to pay'. This is a measure of the users' willingness to engage in maintaining the technology which has been put in place. This is a multi-faceted issue which is beyond the scope of this 'technical' feasibility. Furthermore, it cannot be summarized in general terms, but rather must be considered on the local level in each location. It suffices here to note a number of additional environmental and technical factors which impact significantly on users' willingness to pay, and which are the case fairly consistently across the board.

The first and perhaps obvious observation is that sand dams should be meeting a need which existing solutions do not adequately address. Sand dams are used for a range of different purposes (domestic, livestock, gardening, etc.) but it is important the sand dam provides a service which is not met elsewhere, or else the sand dam risks being redundant and/or surplus to requirements. An example from the author's experience is where sand dams in the Am Dam region of Chad (Section 6.1) were constructed close to villages which already had functioning boreholes with sufficient capacity for domestic. They were intended to supplement the boreholes, but they ended up being superfluous, and as a result the users did not prioritise their maintenance and repair.

The second factor is the distance that the sand dam is from the users. Stern and Stern (2011:2) provide a helpful backdrop to understand this factor:

> *"Sand dams are generally built in remote rural areas without supportive infrastructure… [Users] are also familiar with getting water from sand, as their families have been doing this for generations. Many of them walk miles every day to their 'hole' and may spend hours in a queue waiting for their turn to draw water."*

The 'water burden' placed on a community is a daily experience for many in arid rural contexts. As a result of this users are typically more influenced in their decision making by the distance required to collect water than they are by the quality of the water that they collect, and as such it is important that sand dam locations are within reasonable distance of communities. An exact distance cannot be recommended, since this is usually highly context dependent. However, the sand dam should usually not be further from the users (their village) than existing unimproved year-round water points (such as scoop holes in riverbeds)

The third and final factor mentioned here is the ease with which the sand dam can be accessed by the local population. Since sand dams are preferably located on natural narrowing and rock outcrops (Section 5.5) this can present difficulties of access to collect water. This is very much a local/siting level issue, but it does need to be factored in. Stern and Stern (2011:5) summarise as follows: “the location should be easily accessible to aid in the construction, use, and maintenance of the dam.” Forzieri et al. (2008:83) also recommend constructing sand dams on existing road and communications networks, both to aid during the implementation phase, but also to aid accessibility for usage.

## 5.7. Feasibility framework: affordability

This concludes the technical analysis for affordability, which is encapsulated in the feasibility framework in Figure 24, with 3 key parameters: **Resource Availability**, **River Morphology** and **Willingness to Pay.**

*Figure 24: Feasibility framework for affordability*

| 3. AFFORDABILITY | | |
|---|---|---|
| | **3A Resource availability** | |
| | i. **Cement**: Is cement available locally at a good price?<br>ii. **Local materials**: Can rocks, sand &water be collected nearby?<br>iii. **Local labour**: Are >20 households able to provide labour? | IF ALL YES<br>→ 3A satisfied<br>OTHERWISE<br>→ 3A not satisfied |
| | **3B River morphology** | |
| | i. **Accessible bedrock**: is the riverbed <3 metres thick at site?<br>ii. **Viable river width**: is river less than 25 metres wide at site?<br>iii. **Natural narrowing**: is there a natural narrowing at the site?<br>i.e. the $\alpha$ coeff. Is high, $\alpha = 28\frac{n.W.L}{h.W_{dam}^2}(D - 0.6 + \frac{0.1025}{n})$ | IF ALL YES<br>→ 3B satisfied<br>OTHERWISE<br>→ 3B not satisfied |
| | **3C Willingness to Pay** | |
| | i. **Pertinence**: are users’ water needs already sufficiently met?<br>ii. **Proximity**: is site closer than existing unimproved water points?<br>iii. **Accessibility**: is the site easy to access for water collection? | IF ALL YES<br>→ 3C satisfied<br>OTHERWISE<br>→ 3C not satisfied |

# 6. Data collection and results

## 6.1. Existing sand dams

Chad has little history of sand dam implementation. Following a thorough investigation, the author found that only three sand dams have been constructed in Chad to date. These were undertaken by Islamic Relief (Secour Islamique) Chad in 2013-2014 in the Haouish Sub-Prefecture, 150km southwest of Hadjer Hadid, and 160km south from Abeche (Figure 26Figure 25). A survey trip was conducted on Tuesday 9th May 2017 to visit all three sites and assess the sand dams. The author was accompanied by the project manager who undertook the sand dam project. None of the sand dams were functioning at the time of the visit. This was predominantly because they had been built to support follow-up gardening projects which were undertaken, and the communities already have domestic water supply through boreholes. However, one of the sand dams had been destroyed by the river, and on inspection the cement used had no iron reinforcement in it which accounts for its weakness. Islamic Relief produced a brief video of these sand dams which is available See photos below of the three sand dams:

*Figure 25: Haouich location with respect to Hadjer Hadid*

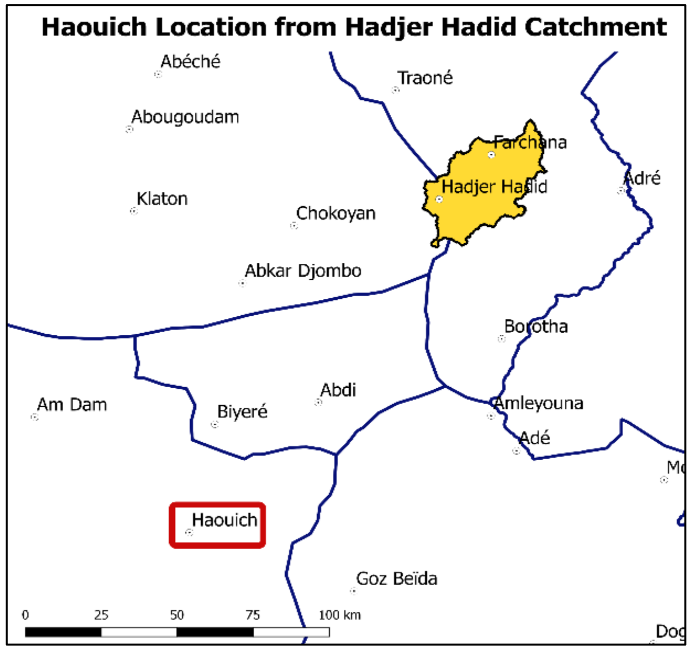



*Figure 26: Photos from Haouich Zaribe, Haouich Town and Am Talata 3*

Summary information for these three sand dams is compiled below in Table 8 and the lessons learned from this visit are mentioned further in Section 8.2.

*Table 8: Information about three sand dams in the Haouich region*

| Name of Village | Date Built | GPS Coord. | Alti-tude | Dist. from Village | Other water points | Purpose | Slope of river bed | Dimen-sions of dam | Sand Accum-ulation? | Reason for not working | Sacs of Cem-ent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Haouich Zaribe** | Oct-Dec 2013 | 12.3977N 20.9274E | 510m | 0.7km | Two bore-holes | Irrigated Gardens | 2% | 18m wide, 2m high | Yes, in 2 rainy seasons | Tap removed | 180 |
| **Haouich Town** | Oct-Dec 2013 | 12.4297N 20.9548E | 502m | 1.5km | Water tower & two bore holes | Irrigated Gardens | 1.5% | 32m wide, 2m high | Partial, though silts are present | Tap removed, perhaps siltation | 270 |
| **Am Talata 3** | Dec 2013 - Feb 2014 | 12.4389N 21.1214E | 521m | 1.2km | ?? | Irrigated Gardens | 1% | 35m wide, 1.5m high | N/A | sand dam Destroyed, Poor Build Quality | 316 |

## 6.2. GIS DATA COLLECTION AND PROCESSING

This research has made extensive use of Geographic Information Systems (GIS) as a tool to compile, process and analyse data. The open-source software Quantum GIS (QGIS) was used to setup a database for Eastern Chad. Data to undertake this was drawn from a number of sources:

1) **Topographical data** was acquired from two sources. Initially the research used Global Digital Elevation Modelling (DEM) produced by the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), which is a high resolution instrument located on the Terra satellite. However, during the research the Shuttle Radar Topography Mission (SRTM) released an updated sample for the region under consideration. This 2017 data boasts better land elevation data, improved from 3 arc seconds (90 metres) to 1 arc second resolution (30 metres), and as such this was mostly used in this research. Both the ASTER and the SRTM data was downloaded from the United States Geological Survey (USGS) website, https://earthexplorer.usgs.gov/. This data was applied to QGIS algorithms and processes (including SAGA, GRASS, and TauDEM plugins) to derive key information, including the following:

- Breaking down the Eastern Chad region into catchment areas, with dividing watersheds; from which the Assounga catchment was isolated. Within this the Hadjer Hadid catchment was chosen as the geographic scope of this research (see Section 6.4).
- Identifying stream and river channels for the catchment area, and using vector analysis to categorize river channels based on their slopes.
- Calculating catchment areas and mean catchment slopes for proposed sand dam sites;

2) **Geological and demographic data** was provided by Réseau Tchad (https://reseau-tchad.org), an initiative in partnership with the “Ministère de l'Elevage et de l'Hydraulique” (Ministry of Livestock and Hydrology). Their goal is to integrate hydrogeological data into a single national framework, providing mapping resources and both public and private sector training. They willingly made their GIS databases available for this research, and in particular the following was key to this research:

- the probable location of faults and fractures in Eastern Chad, determined by complex analysis of satellite imaging data undertaken by Reseau Tchad partners;
- Actual river courses (as compared to theoretical stream channels derived from DEM data);
- Vector, Lines and Polygon Data for locations of roads, villages, towns, refugee camps, political boundaries,
- Hydrological data including the location of boreholes, springs, open wells, lakes, etc.

In addition to these resources, local IAS staff had previously undertaken community surveys across the region, which provided detailed demographic data on villages, as well as information about their access to water points.

3) **Satellite photograph** and remote imaging data is from Google Earth (Digital Globe, 2017), and Google Earth Pro software was used to provide birds-eye photographs for the sand dam locations identified, and also additional GPS references and coordinates. Each location visited (Section 6.4) was supplemented with satellite imagery to ensure a higher level of accuracy. Google Earth was used in conjunction with QGIS, cross-checking data between the two platforms to ensure accuracy. Satellite data was used in conjunction field data, with some key functions:

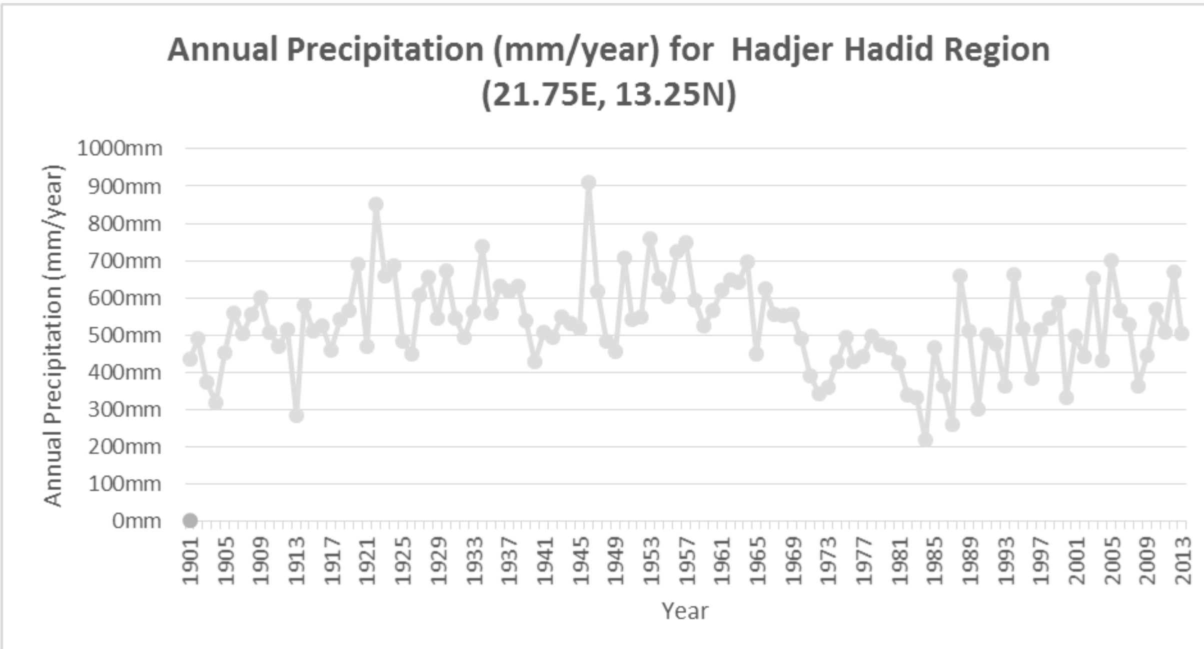
- Providing distance estimates, e.g. between sand dams and the nearby users (villages), as well as marking out the perimeters of villages;
- Marking out the throwback for each sand dam site, and the dimensions of the sand reservoir behind the dam. This was done in conjunction with data collected in the field, which provided more precise contour measurements to ensure the correct size of reservoir.

## 6.3. RAINFALL DATA

Rainfall data for the region is limited. There are very few weather stations in the Sahel region. The nearest functioning stations to the region are Abeche, Goz Beida, Geneina (Sudan), and historically there was also a station in Adre. However, the region of Hadjer Hadid itself does not have its own rain gauge, and as such the rainfall data relies on interpolating from the available nearby sources. So rather than using the raw precipitation data from these nearby weather stations, gridded data is used, where interpolation algorithm estimate rainfall on a grid system, based on nearby data points. However, since data points in Chad and Sudan are very sparse, errors may be significant.

This research has made use of interpolation undertaken by Schneider et al. (2015) in partnership with the Global Precipitation and Climatology Centre (GPCC) to provide gridded data for Hadjer Hadid. Specifically, annual total precipitation data from 1901 to 2013 was collected, enabling easy calculation of mean and standard deviation rainfall, both historically and in recent years. The data set is recorded in Appendix 10.1, and is presented graphically in Figure 27 below:

*Figure 27: Graph showing annual precipitation for Hadjer Hadid from 1901 to 2013*



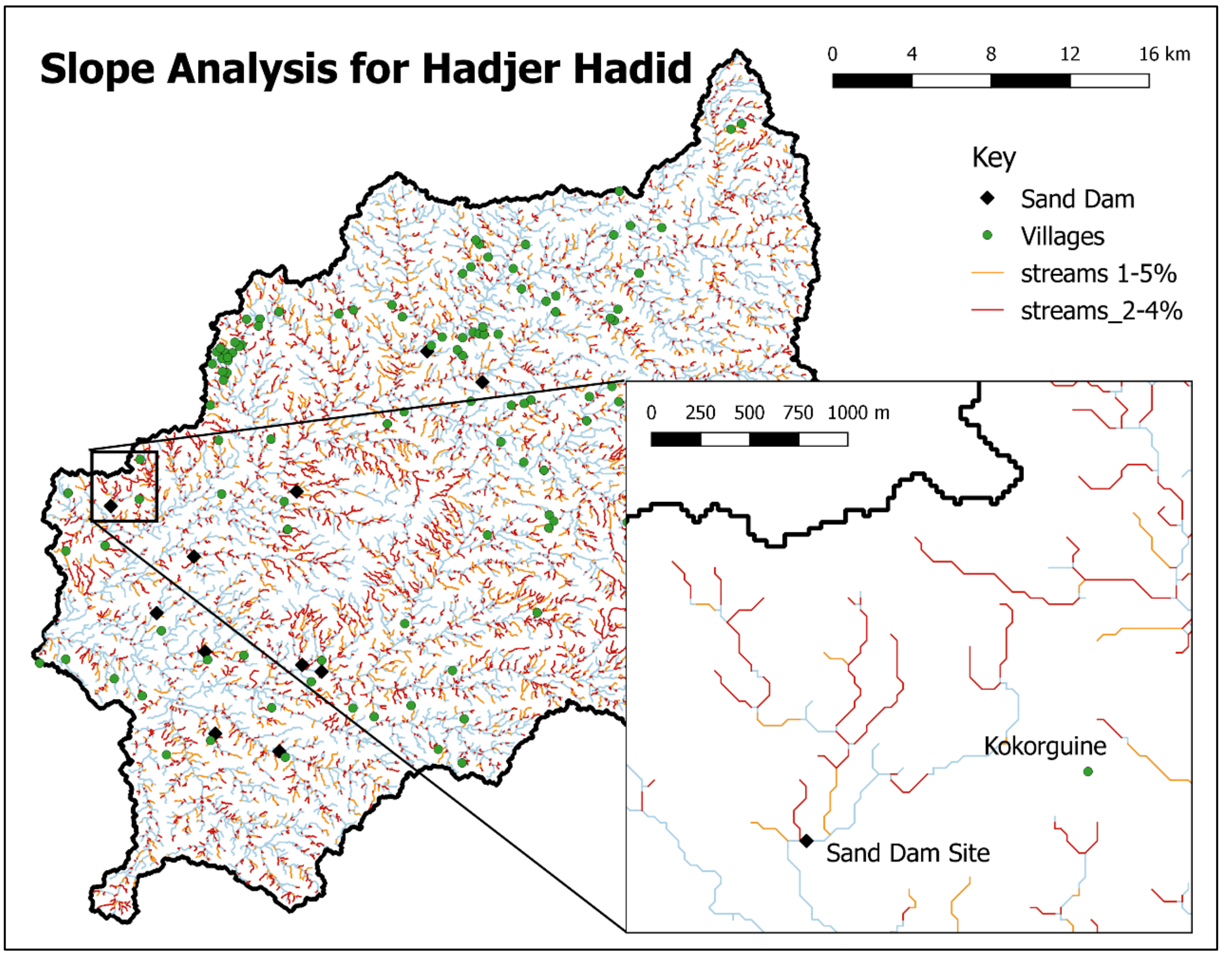

## 6.4. SITE IDENTIFICATION

This research focuses on sand dam feasibility with the prescribed geographic region set out in 1.3. This feasibility assessment is undertaken on multiple levels (as explained in Section 2.4.2) which are applied to the Eastern Chad context in the following way:

- The macro/regional level encompasses wider Assounga catchment in Eastern Chad, and more specifically the Hadjer Hadid catchment area;
- The mid/catchment level considers the sub-catchments within the Hadjer Hadid catchment, determined by favourable stretches of river;
- The micro/siting level addresses specifically the location of the dam on a given river, with a view to selecting the most favourable location for construction.

The macro/regional aspect required a predominantly desk-based approach. However, the mid/catchment level and micro/siting level require the identification of prospective sand dams sites which are used as being representative of the region. This allows the inclusion of site and catchment specific criteria in the regional feasibility study, and it also outputs recommended sites. However, a method is required to identify such sites. The research initially proposed a GIS survey of the region to identify sites, by making use of remote imaging and DEM analysis in conjunction with demographic information (user locations and populations). A similar 'top-down' approach was employed by Forzieri et al. (2008) and Gijsbertsen (2007). Based on the results of Chapter 0 slope analysis was conducted on the river channels derived from the DEM. The goal was to isolate stretches of river with slope between 1 and 5% (based on the findings of 4.4), and optimally between 2 and 4%. The results are presented in Figure 28 below.

*Figure 28: Slope analysis for the Hadjer Hadid catchment area*




The Fig. # provides the stream network for the Hadjer Hadid catchment, with highlighted slopes of 2-4% (red) and more broadly 1-5% (orange). Additionally, villages are recorded in green. Inset the case of Kokorguine can be seen, with the sand dam site located within a reasonable distance from the village, at the tail end of a stretch of river with favourable slopes. Areas with high density of favourable river slopes, in conjunction with satellite data from Google Earth (Digital Globe, 2017), provided a framework for site identification. This process was undertaken in consultation with local knowledge, including the local government, traditional authorities, key stakeholders (the area pump mechanic, community leaders), and local IAS employees. Follow on from this desk-based survey, it was necessary to undertake field visits, both to verify/discount proposed locations, and also to collect relevant field data to be used in the feasibility study. Out of about two dozen prospective sites, visited between the dates of 14th and 22nd of June, this process yielded 11 sites which were considered favourable based on the following criteria:

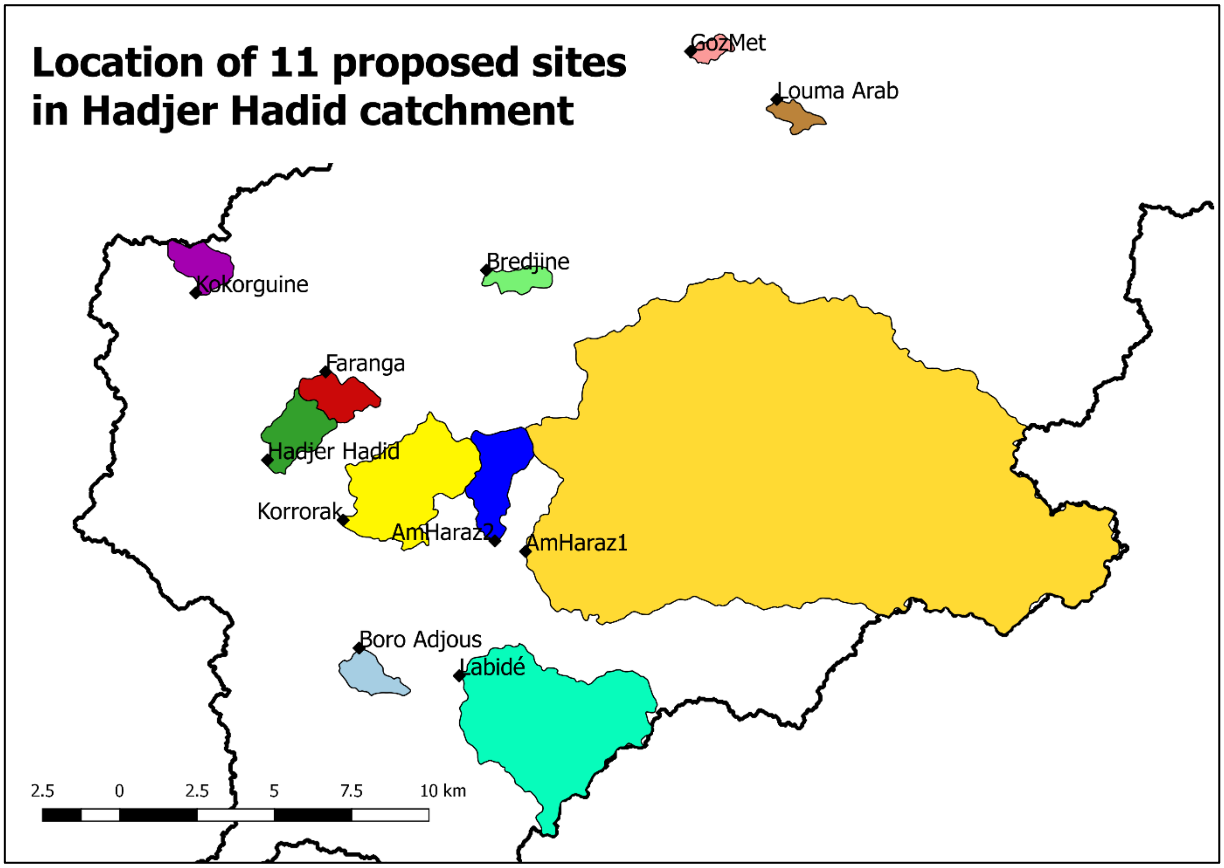
1. appropriate riverbed slopes (Section 4.4)
2. Natural narrowing (Section 5.5) and appropriate width of river (Section 5.4)
3. Proximity to a population centre, with sufficient households (Section 5.2)
4. No other proximate improved water points (Section 5.6)
   OR insufficient improved water points to serve existing user population.

These locations can now be thoroughly assessed and applied to the feasibility framework put forward in this research for a fuller analysis. The sites are presented below in Table 9 and Figure 29.

*Table 9: Proposed sites for sand dam construction in Hadjer Hadid catchment*

| sand dam Location | Date of Visit | GPS Coordinates | | Elevation | No. of Households | Water Point | School? | Health Centre? |
|---|---|---|---|---|---|---|---|---|
| Am Haraz1 | 15/6/17 | N13.24.36 | E21.44.65 | 722 | 60 | None | No | No |
| Am Haraz2 | 15/6/17 | N13.24.55 | E21.44.10 | 762 | | | | |
| Boro Adjous | 14/6/17 | N13.22.69 | E21.41.63 | 729 | 158 | 1 Borehole, functioning | No | No |
| Bredjine | 22/6/17 | N13.29.26 | E.21.43.97 | 709 | 70 | 1 Borehole, broken down | Yes | No |
| Faranga | 22/6/17 | N13.27.56 | E21.41.25 | 740 | 75 | None | No | No |
| Goz Met | 21/6/17 | N13.33.10 | E21.47.54 | 786 | 145 | none | Yes | No |
| Hadjer Hadid | 20/6/17 | N13.25.97 | E21.40.10 | 761 | approx. 1000 | 1 Borehole, broken down | Yes | Yes |
| Kokorguine | 20/6/17 | N13.28.81 | E21.38.91 | 707 | 650 | 1 Borehole, broken down | Yes | No |
| Korrorak | 19/6/17 | N13.31.65 | E21.42.21 | 707 | 48 | None | No | No |
| Labidé | 14/6/17 | N13.22.24 | E21.43.44 | 740 | 123 | None | Yes | No |
| Louma Arab | 21/6/17 | N13.32.25 | E21.49.01 | 696 | 74 | 1 Borehole, broken down | Yes | No |

*Figure 29: Location of proposed sand dams and their catchments*




## 6.5. Field Data

The sites listed above were visited and at each location a full sand dam assessment was conducted, which typically took 2-4 to conduct. Here an overview of this process is provided to describe how the data was collected:

*Figure 30: Geotech shaker*

www.geotechenv.com

1) **Coordinates and Positioning**: GPS coordinates were taken at each site as well at the nearby village centre. This enabled straightforward geo-referencing with QGIS and Google Earth, and also enabled simple calculation of the distance between the sand dam and users.

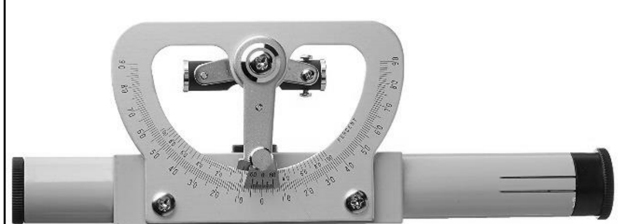
2) **Sediment Analysis** – guidance provided by Maddrell and Neal (2012:12-13) was used for sand analysis. At each site, three samples of sand were taken. A Geotech sand shaker (see Figure 30) and mechanical scales were used to filter the sand and categorize the different grades of sediment. Below is a table of these results (Table 10).

*Table 10: The results of the sediment analysis for each site*

| | | | **Result from sediment test, in grams for each filter layer (when starting with 200g); mean from three samples at each location** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grade of Sediment | Filter No | Filter Size (mm) | AmHaraz1 | AmHaraz2 | Bredjine | Boro Adjous | Faranga | Goz Met | Hadjer Hadid | Kokourgine | Korrorak | Labidé | Louma Arab |
| Large Gravel | 187 OPN | 5 | 0 | 0 | 1.2 | 0 | 0 | 0 | 0.8 | 0 | 0 | 2 | 0 |
| Gravel | 90 OPN | 2.5 | 0.1 | 2.7 | 0 | 7.5 | 3 | 1.1 | 1 | 0.4 | 3.9 | 3.2 | 3 |
| V. Coarse Sand | 40 OPN | 1 | 5.1 | 12.4 | 10.4 | 35 | 17.6 | 22.2 | 7.9 | 4.5 | 7.5 | 20.5 | 40.6 |
| Coarse Sand | 20 OPN | 0.5 | 119.4 | 135 | 125.1 | 106.5 | 132 | 135.8 | 92 | 76 | 126.9 | 100.4 | 107 |
| Medium Sand | 09 OPN | 0.2 | 40.5 | 26.7 | 43.2 | 18.8 | 28.7 | 29.8 | 53.8 | 64.6 | 38.7 | 30.6 | 24.8 |
| Fine Sand | 046 OPN | 0.1 | 30.2 | 21 | 16.2 | 28.4 | 13.1 | 8.8 | 34.7 | 46.6 | 21.6 | 37.2 | 18.2 |
| Silt | 0.24 OPN | 0.05 | 2 | 0.8 | 3.5 | 1.9 | 5 | 0.6 | 7.7 | 6.6 | 1.2 | 3.8 | 5.6 |
| Clay | Pass through | | 0.2 | 0.1 | 0 | 0.3 | 0.1 | 0 | 0.8 | 0.8 | 0 | 0.7 | 0.4 |
| Total | Sum of Above | | 197.5 | 198.7 | 199.6 | 198.4 | 199.5 | 198.3 | 198.7 | 199.5 | 199.8 | 198.4 | 199.6 |
| Loss during experiment | | | -1.3 | -0.7 | -0.2 | -0.8 | -0.3 | -0.8 | -0.7 | -0.3 | -0.1 | -0.8 | -0.2 |

***3) Slope Calculations**: the riverbed slope both upstream and downstream was calculated, using topographic Abney level. The type used was CST/Berger's 5X Magnifying 17-645 which can be seen in Figure 31. The method is described in RAIN (2007:13), and illustrated in the*

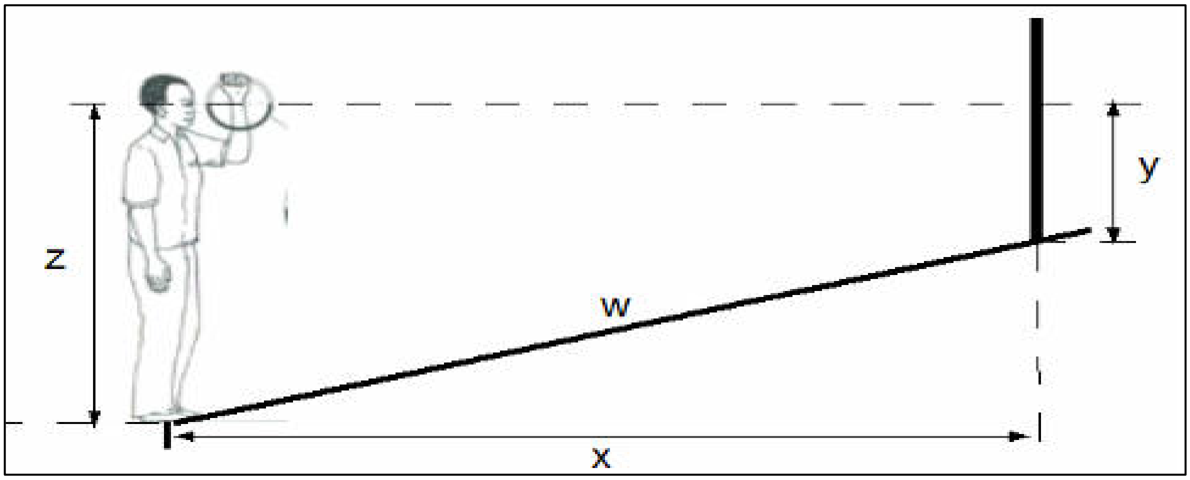
*Figure 31: CST/Berger 17-645 5X Magnifying*



**Source:** www.cstberger.com

Figure 32 below. In our case, a distance (X) of 50 metres was selected; the calculations for Z-Y are calculated, from which the slope is derived.

*Figure 32: Method for calculating the slope of the riverbed*




*[Adapted from: Nissen-Petersen, 2006]*

*Figure 33: Slope calculations downstream and upstream for sand dam sites*

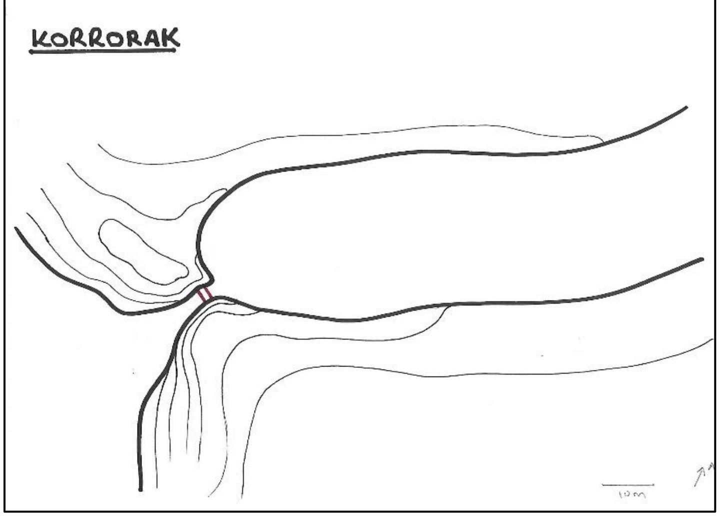
| Location | Upstream | | Downstream | |
|---|---|---|---|---|
| | Z-Y (cm) | Slope (%) | Z-Y (cm) | Slope (%) |
| Am Haraz1 | 65 | 1.30% | 30 | 0.60% |
| Am Haraz2 | 107 | 2.14% | 88 | 1.76% |
| Boro Adjous | 62 | 1.24% | 73 | 1.46% |
| Bredjine | 64 | 1.28% | 46 | 0.92% |
| Faranga | 75 | 1.50% | 81 | 1.62% |
| Goz Met | 140 | 2.80% | 109 | 2.18% |
| Hadjer Hadid | 44 | 0.88% | 58 | 1.16% |
| Kokorguine | 136 | 1.72% | 308 | 6.17% |
| Korrorak | 107 | 2.14% | 35 | 0.70% |
| Labidé | 39 | 0.78% | 47 | 0.94% |
| Louma Arab | 74 | 1.48% | 89 | 1.78% |

4) **Probing Rod Measurements**: a probing rod was used to calculate the depth from the riverbed to the underlying bedrock. A rod was 25mm wide and 3.5m long was commissioned locally, by welding together disused car axles. The probing rod provides information about the depth of the bedrock, but also the nature of the bedrock based on the sound that impact makes (a 'ringing' sound represents rock and a 'thud' represents clay type soil). The level of water can also be estimated by registering the point at which the rod is wet. The probing rod was used at the site to calculate depths presented in sketches of the channel cross-section. Probes were also undertaken upstream of the proposed dam site, at 10 meter intervals, in order to have a fuller understanding of the sand reservoir volume.

*Figure 34: Photo of using the probing rod in Korrorak*

5) **Measurements and Dimensions**: measurements were made at the sites, in particular to assist with dimensioning the proposed dam. The width of the dam at various heights was considered, both to estimate the height of the dam, and also to consider what volume of cement would be required. On site sketches were made for the cross-sectional area, as shown in the data presentation (Section 6.6). In addition reservoir dimensions were estimated by making an aerial view of the area, an example of which is provided in Figure 35. Ultimately it was preferred to rely on Google Earth to draw these plans for the research; field sketches were used to corroborate and clarify.

*Figure 35: Aerial view of Korrorak sand dam reservoir*

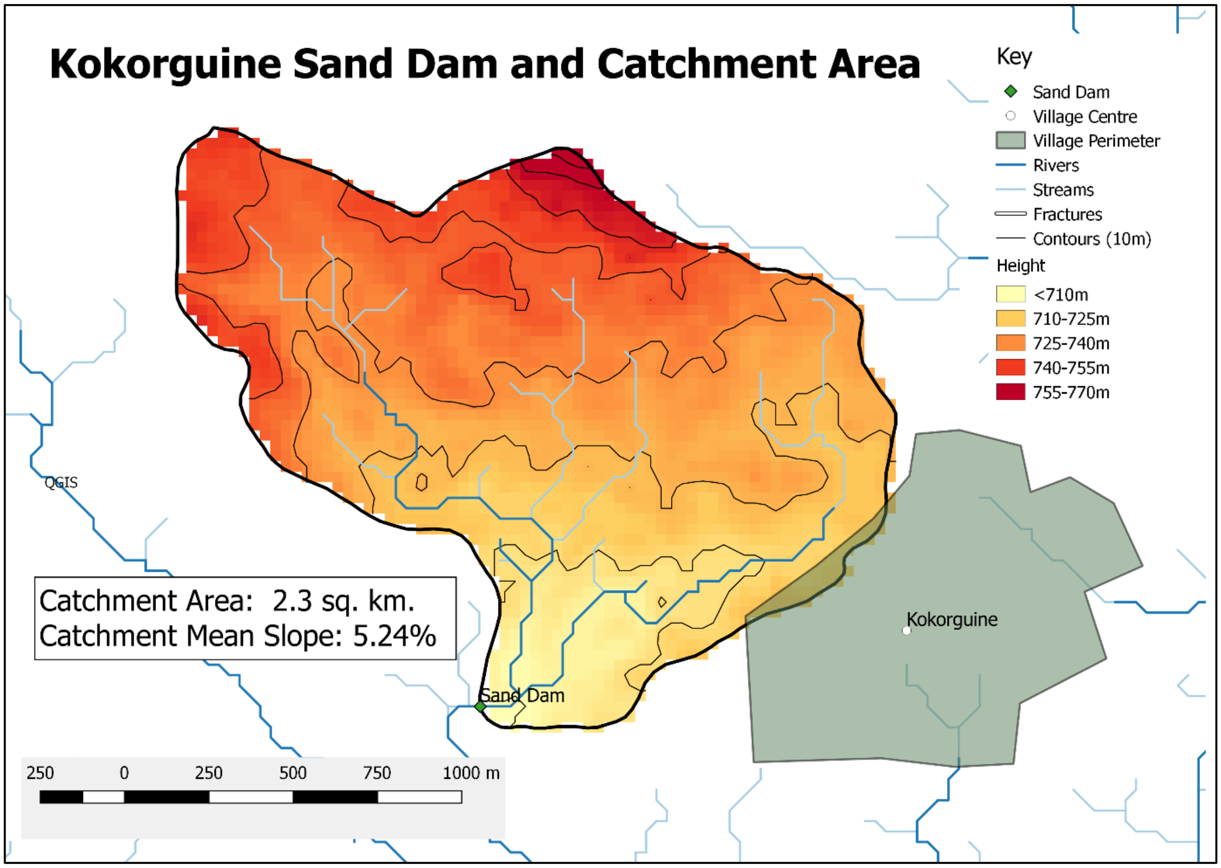



8) **Miscellaneous**: in addition to the specific areas mentioned above, there were a great many of other details which were recorded. This included vegetation density and types lining the river, the presence of scoop holes in the riverbed, and the depth at which water could be found, the ease of access to the sand dam site, the apparent geology of the region, among other notes.

## 6.6. Data presentation

The data was collected and amalgamated using QGIS, Google earth and Excel. QGIS was used to calculate the catchment area behind the dam for each site. Fig. # provides an example:

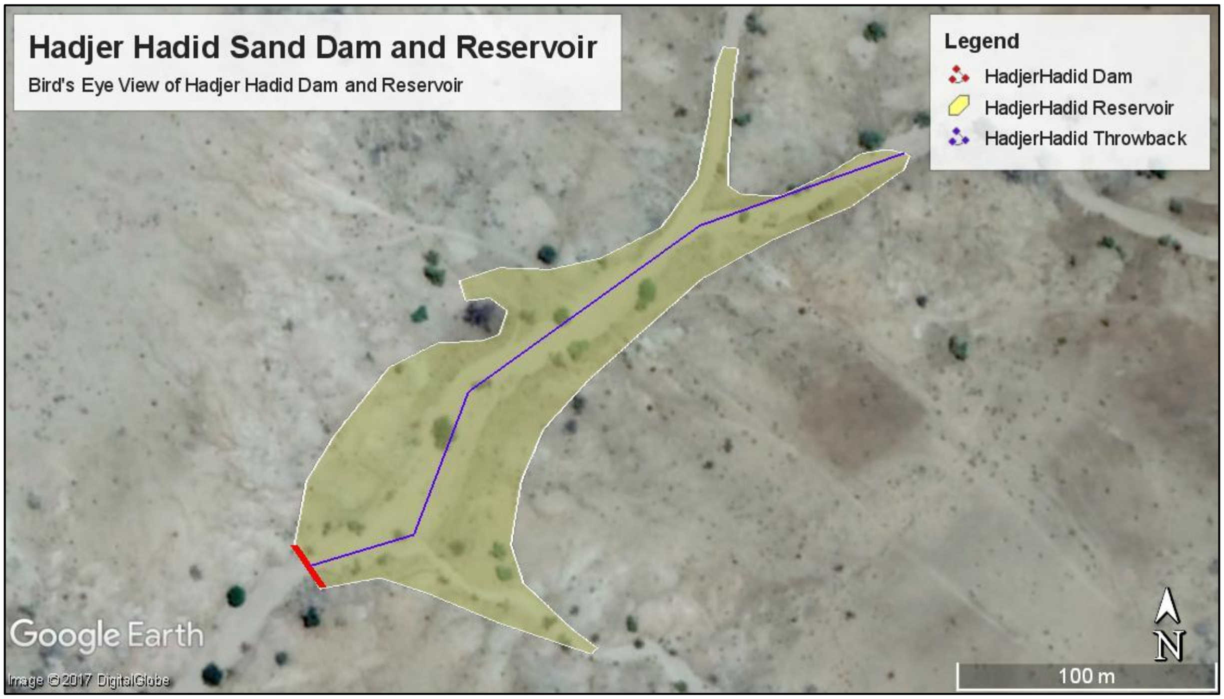
*Figure 36: The catchment area for the Kokorguine proposed site*




The map provides a helpful graphical illustration of the area. It includes elevation data and contours, as well as streams and rivers. The village is also marked on the map. Fractures are also included, though Fig. # does not have any present (however see Section 7.2.1 for its relevance). Using this data the catchment area and the mean catchment slope are calculated for each site.

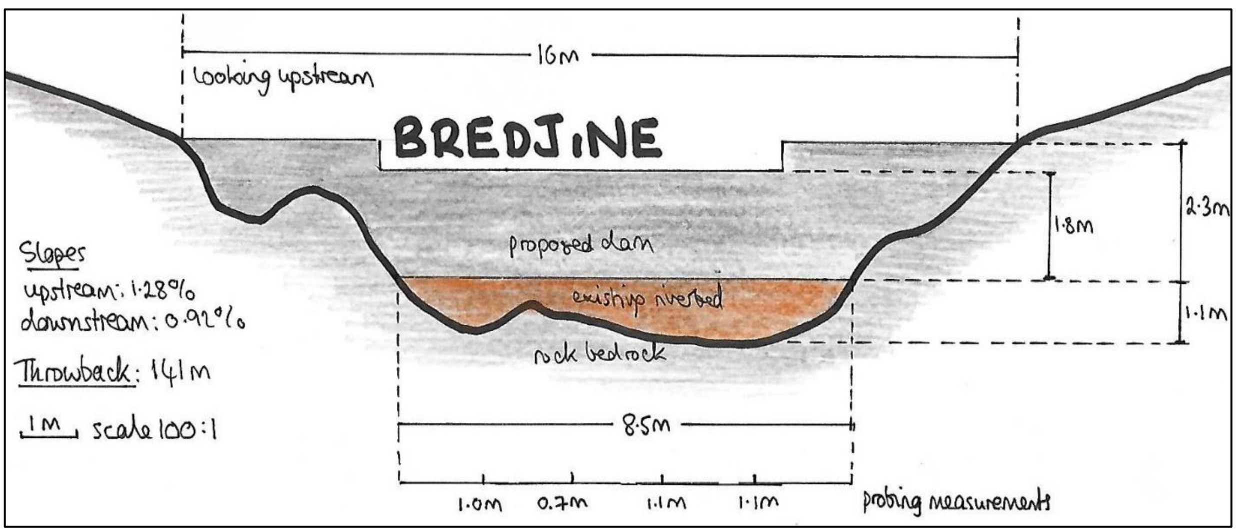
The sand reservoir behind is determined by the throwback, which is determined by the topography of the land, and can be derived from the dam height and the river upstream slope. However in some cases this may vary, if for example there was sudden steepening into a gorge at a relevant distance from the dam. This was marked out using the Google Earth software. In conjunction with field data it was possible to calculate the likely dimensions of the sand dam reservoir that would build up behind the dam. This provides a means to estimate the total area of the sediment that would build up, and through this also to calculate the total volume of water that can be stored behind the dam. An example of this process is illustrated below in Figure 37.

*Figure 37: Hadjer Hadid sand reservoir area and throwback*




Finally, the detailed plans for the dam siting and dimensions is presented as a cross-section of the river channel, and incorporates a range that was collected for the research, illustrated in Figure 38:

*Figure 38: Cross-section of Bredjine river with sand dam dimensions*




Finally, based on all the data collection, relevant information about each site was compiled ready for full analysis (in Chapter 7). This is summarized in the table below and will be used extensively in the data analysis to establish sand dam feasibility:

*Table 11: Summary information for each of the proposed sites*

| | Dam Dimensions (m) | | | | Slope (%) | | Sand reservoir | | | Village Dist. | | Catchment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Width of river (at riverbed) | Width of river (at dam height) | Height of Dam (from riverbed) | Depth of riverbed (to bedrock) | Slope upstream (%) | Slope downstream (%) | Throwback (m) | Area of Reservoir (sq. m) | Max Width of Reservoir (m) | Distance to Village Centre (km) | Distance to Village Edge(km) | Area (sq. km) | Mean Slope (%) |
| Am Haraz1 | 6 | 24 | 1.7 | 2 | 1.3% | 0.6% | 110 | 4,111 | 26 | 0.6 | 0.2 | 149 | 6.3% |
| Am Haraz2 | 5.5 | 19 | 2.5 | 1 | 2.1% | 1.8% | 145 | 4,301 | 42 | 1.1 | 0.5 | 4.5 | 8.7% |
| Boro Adjous | 6 | 16 | 1.1 | 0.9 | 1.2% | 1.5% | 161 | 4,803 | 52 | 0.4 | 0.3 | 1.9 | 3.9% |
| Bredjine | 8.5 | 16 | 1.8 | 1.1 | 1.3% | 0.9% | 226 | 5,200 | 32 | 0.7 | 0.2 | 1.4 | 7.5% |
| Faranga | 2 | 15 | 3.5 | 0.4 | 1.5% | 1.6% | 46 | 725 | 22 | 0.3 | 0.1 | 2.6 | 5.1% |
| Goz Met | 5 | 15 | 2.5 | 0.4 | 2.8% | 2.2% | 104 | 2,007 | 27 | 0.4 | 0.1 | 0.8 | 3.4% |
| Hadjer Hadid | 7.5 | 20 | 2 | 1.4 | 0.9% | 1.2% | 293 | 12,946 | 74 | 1.2 | 0.6 | 3.3 | 4.3% |
| Kokorguine | 26 | 24 | 2.5 | 0 | 1.7% | 6.2% | 145 | 3,982 | 37 | 1.3 | 0.8 | 2.3 | 5.2% |
| Korrorak | 2 | 18 | 3 | 0.5 | 2.1% | 0.7% | 166 | 5,803 | 48 | 0.5 | 0.2 | 11.0 | 7.9% |
| Labidé | 18 | 26 | 2.5 | 2 | 0.8% | 0.9% | 576 | 27,503 | 88 | 0.4 | 0.3 | 21.5 | 3.8% |
| Louma Arab | 9 | 16 | 3.5 | 1 | 1.5% | 1.8% | 241 | 4,242 | 32 | 0.8 | 0.5 | 1.0 | 3.8% |

The above data is presented for each respective site in Appendix 10.2 with each of the aforementioned diagrams and maps in each case. This provides a basis for now looking at the feasibility study itself, making use of the technical analysis undertaken in

# 7. FEASIBILITY STUDY

## 7.1. WATER SUPPLY

We will now apply the feasibility framework in Figure 15 (copied again below) to evaluate the water supply criteria for the Hadjer Hadid catchment, by considering first the impermeability of the bedrock (1A) and secondly the appropriateness of the rainfall (1B).

<table>
<tr><td rowspan="4">2. STORAGE CAPACITY</td><td colspan="2">2A RESERVOIR VOLUME</td></tr>
<tr><td>i. Is the reservoir volume sufficient for the purpose?<br>$V_S(eff) = 1.4\frac{n}{4}(D - 0.6 + \frac{0.1025}{n}) \times W \times L$</td><td>YES → 2A satisfied<br>NO → 2A not satisfied</td></tr>
<tr><td colspan="2">2B SEDIMENT ACCUMULATION</td></tr>
<tr><td>i. Is sand (grain size >0.2mm) naturally present in riverbed?<br><br>ii. Does the catchment have a mean slope >2%?<br>AND<br>Does the riverbed have a slope of between 1% and 5%?</td><td>YES → 2B satisfied<br>NO → need to answer ii.<br><br>IF BOTH YES<br>→ 2B satisfied<br>OTHERWISE<br>→ 2B not satisfied</td></tr>
</table>

### 7.2.1. BEDROCK IMPERMEABILITY

The geology of eastern Chad can be assessed by reviewing hydrogeological maps made available by Reseau (see Section 6.2). The hydrogeological maps for the region is presented in

Figure 39, with an additional overlay to show the catchment area for Hadjer Hadid and the proposed sand dam sites. Please also note the inset rock type. It can be seen in

Figure 39 that almost the entire area of the Hadjer Hadid catchment is classified as 'granites, migmatites, rare gneiss, schists'. By applying the impermeability classification in Table 4 we return a 'maybe' result, which requires us investigate further to assessing whether there are any fractures or faults along the riverbed for any of the proposed sites. By looking at the catchment area maps for the eleven prospective sites (available in Appendix 10.2) and observing the location of fractures and faults, we are required to discount on of the sites, Labidé, with the fracture location visible in Figure 34. The fracture runs along the valley very close to the riverbed, and in light of its proximity to the proposed sand dam there is significant risk that the sand reservoir would suffer water loss through groundwater infiltration into this fracture. As such this site cannot be considered suitable.

*Figure 39: Hydrogeological map of the Hadjer Hadid catchment*

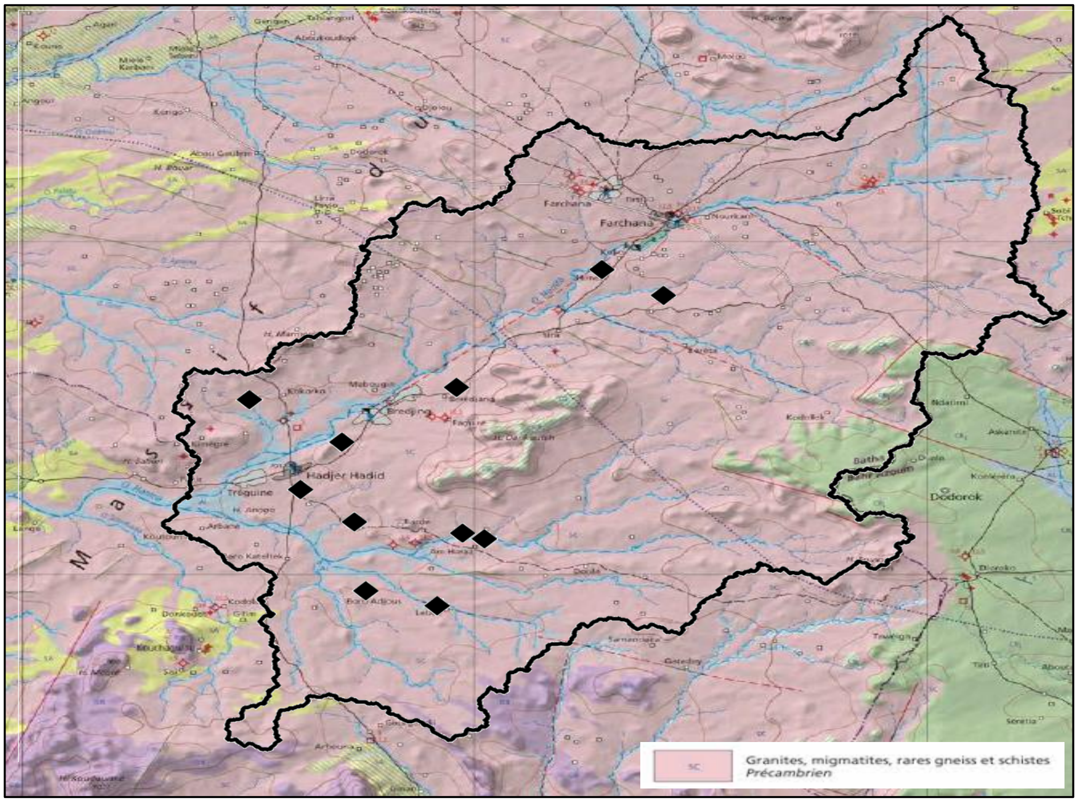
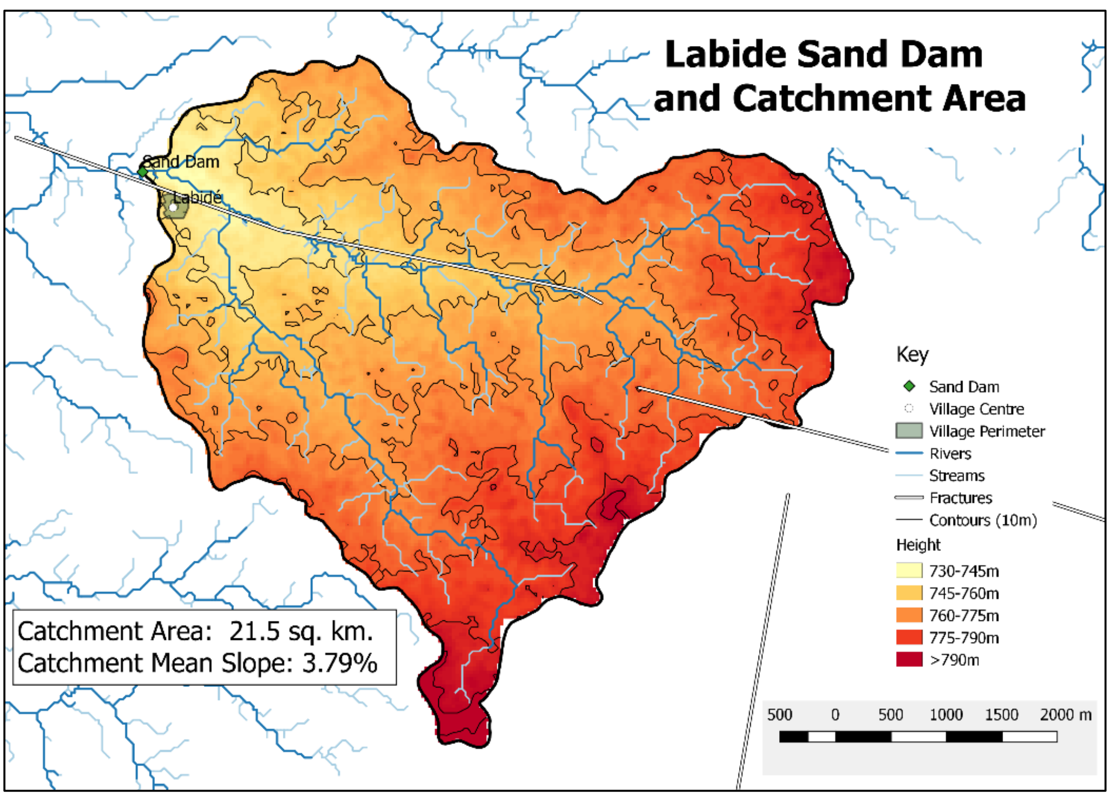
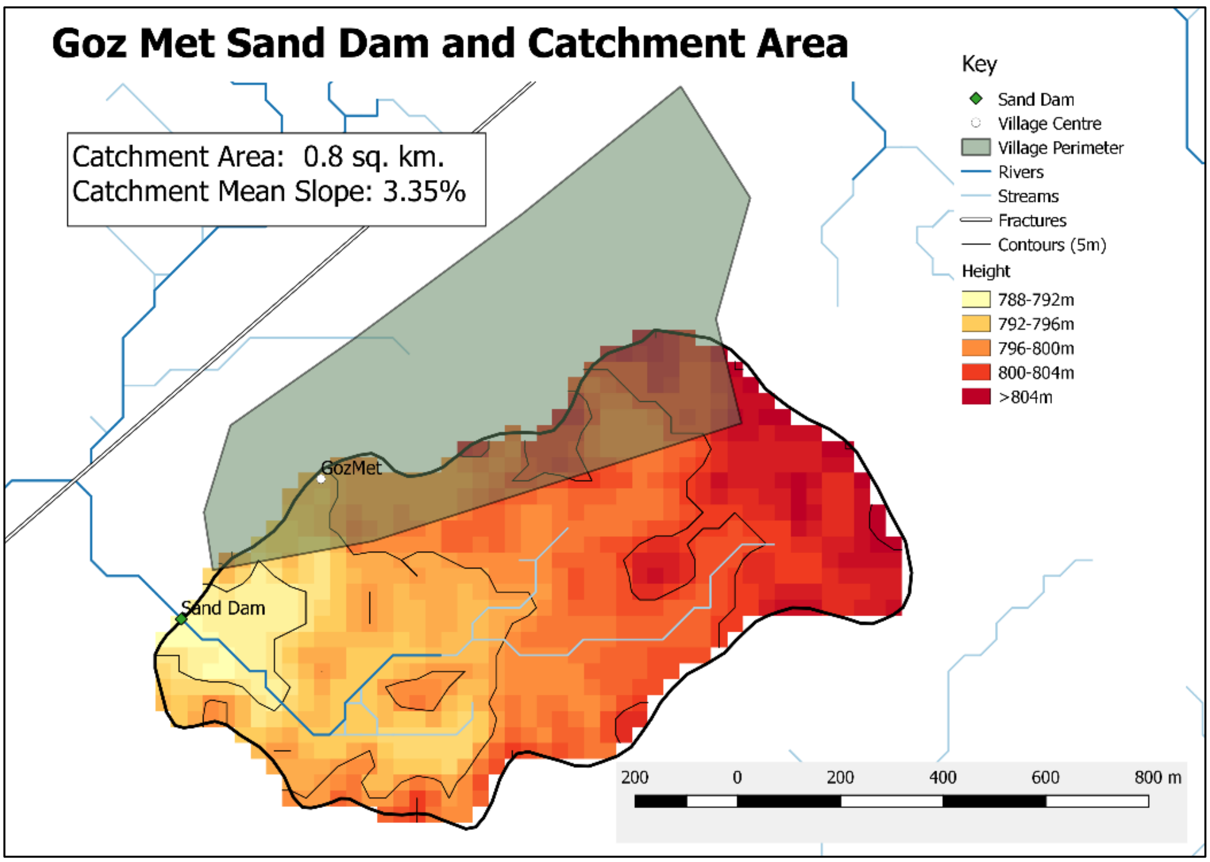



*Figure 40: Labidé catchment area with fracture visible*



The only other location which poses some concern is Goz Met, which has a fracture running along the course of a valley approximately 350 metres away from the dam, as visible in Figure 41. However, this distance is too considerable for the fracture to affect the permeability of the sand reservoir, and indeed it is located downstream rather than upstream from the sand dam site. As such it does not need to be factored in. We can conclude that condition 1Aii was satisfied in every case except for Labidé.

*Figure 41: Goz Met catchment area with fracture visible*




Sadly, as mentioned Section 7.4, the timing of the field visits coincided with significant rainfall on previous days, which means information about location of scoop holes in riverbeds close to sand dam was not able to be used, since most of the riverbeds had some level of saturation from the recent rains. It would be appropriate to refine the results to return to the proposed sites at the end of dry season and to gauge the depth of the water in the riverbed, as well as the presence of any scoop holes being used by local communities.

### 7.2.2. Appropriate rainfall

The rainfall must both be sufficient (condition 1Bi) and also be such that the environmental impact of the sand dam is tolerable on the surroundings (condition 1Bii). For the former we must calculate the probability for a given year that the actual rainfall is greater than the volume of rainfall required to fill the sand reservoir, defined as h:

$$P(full) = P(h_i \geq h) \geq 0.95 \quad where \;\; h = \frac{V_s(eff) + E_T + G_c}{A}$$

We are able to assume that $G_c = 0$ in light of our conclusions in regarding the impermeability of the bedrock.. However, it is not straightforward to calculate the evapotranspiration rate for Hadjer Hadid. There was no opportunity to undertake field research to calculate this, and as such this research will make use of data collected in Abeche (close to Hadjer Hadid) by Rivas-Martinez (2007:), and apply the same precipitation to evapotranspiration ratio when applying it to Hadjer Hadid. The mean evapotranspiration for Abeche was estimated as 505mm per square metre, compared with mean rainfall of 518mm. This means that 97.5% of rainfall is lost as evapotranspiration. This figure is comparable to other arid contexts mentioned in literature (Forzieri et al., 2008, Borst & de Haas, 2006). We will express the evapotranspiration as a percentage of rainfall in a given year, $h_i$, since the two are proportional. This must be multiplied by the catchment area for the total to provide a volume. Thus we have the following equation:

$$h = \frac{V_s(eff) + 0.97.5 \times h_i \times A}{A} = \frac{V_s(eff)}{A} + 0.97.5h_i$$

$$P(full) = P(h_i \geq h) = P\left(h_i \geq \frac{V_s(eff)}{A} + 0.97.5h_i\right) = P\left(h_i \geq \frac{V_s(eff)}{0.025A}\right)$$

So for this condition to be satisfied, $\frac{V_s(eff)}{A}$ must be less than 0.025 times the annual rainfall total.

By using rainfall data for the last hundred years (Appendix 10.1) we are able to look at how many occasions there have been when this condition was not met, which gives us a confidence interval for the water supply being sufficient. Using figures for $V_s(eff)$ calculated in Table 13 below, and the area of each respective catchment recorded in Table 11 we are able to show results in Table 12. The lowest annual total rainfall between 1901 and 2013 was 1984 when there was only 220mm of rainfall. However, this is still well above the largest value of h out of our eleven sites in the Hadjer Hadid catchment area: Louma Arab requires 169.3mm per annum of rainfall to fill its sand reservoir. We can thus conclude that for all eleven location condition 1Bi is satisfied. Please note the final column of Table 12, which shows what percentage of discharge is retained by the sand dam, and this can be compared with the results of other countries in Table 5.

*Table 12: Calculating the rainfall required to fill the sand reservoir for each site*

| Location | Total Extractable Volume ($m^3$), $V_s(eff)$ | Total Catchment Area ($m^2$), $A$ | Minimum rainfall threshold $h$ | How many occasions in history $h_i \geq h$ | Mean percentage reduction in discharge from sand dam (%) |
|---|---|---|---|---|---|
| Am Haraz1 | 1600 $m^3$ | 148,908,000 | 0.4 | Never | 0.1% |
| Am Haraz2 | 2800 $m^3$ | 4,513,000 | 24.4 | Never | 4.6% |
| Boro Adjous | 2100 $m^3$ | 1,866,000 | 45.8 | Never | 8.7% |
| Bredjine | 2800 $m^3$ | 1,415,000 | 78.2 | Never | 14.8% |
| Faranga | 600 $m^3$ | 2,569,000 | 9.1 | Never | 1.7% |
| Goz Met | 1100 $m^3$ | 793,000 | 54.2 | Never | 10.3% |
| Hadjer Hadid | 8500 $m^3$ | 3,335,000 | 102.4 | Never | 19.4% |
| Kokorguine | 2400 $m^3$ | 2,289,000 | 41.3 | Never | 7.8% |
| Korrorak | 4200 $m^3$ | 11,027,000 | 15.1 | Never | 2.9% |
| Labidé | 28200 $m^3$ | 21,546,000 | 52.3 | Never | 9.9% |
| Louma Arab | 4400 $m^3$ | 1,033,000 | 169.3 | Never | 32.1% |

We now need to assess condition 1Bii, by looking at whether the demand of water by a given sand dam is environmentally tolerable. The following condition must be satisfied:

$$\sqrt{\left|\frac{\sum(P_i - \bar{P})}{n}\right|} \geq h \quad where\ \bar{P} = \frac{1}{n}\sum_{i=1}^{i=n} P_i$$

In simple terms, the rainfall requirement to fill the sand reservoir must be less than the standard deviation of the rainfall. The latter has been calculated in Appendix 10.1, with standard deviation of rainfall being 121mm historically (1901-2013) and 124mm more recently (1981-2013). When looking at our values of $h$ in Table 12, we can see that only one location (Louma Arab) fails to meet this criteria. This can be explained by the fact that this location proposes having a large dam, and therefore retaining a large volume of water. However, by comparison its catchment area is very small (0.8 sq. km). The environmental impact of this dam would be greater than the standard deviation in rainfall each year, and it is therefore necessary to discount from being a sand dam site. Thus all the sites meet condition 1Bii except for Louma Arab.

## 7.2. STORAGE CAPACITY

We will now apply the feasibility framework in Figure 22 (copied again below) to evaluate the storage capacity criteria for the Hadjer Hadid catchment, by considering first the reservoir volume (2A) and secondly the Sediment Accumulation (2B).

| 2. STORAGE CAPACITY | | |
|---|---|---|
| | **2A RESERVOIR VOLUME** | |
| | i. Is the reservoir volume sufficient for the purpose? $V_S(eff) = 1.4\frac{n}{4}(D - 0.6 + \frac{0.1025}{n}) \times W \times L$ | YES → 2A satisfied<br>NO → 2A not satisfied |
| | **2B SEDIMENT ACCUMULATION** | |
| | i. Is sand (grain size >0.2mm) naturally present in riverbed? | YES → 2B satisfied<br>NO → need to answer ii. |
| | ii. Does the catchment have a mean slope >2%?<br>AND<br>Does the riverbed have a slope of between 1% and 5%? | IF BOTH YES<br>→ 2B satisfied<br>OTHERWISE<br>→ 2B not satisfied |

### 7.2.1. RESERVOIR VOLUME

Based on the feasibility framework in Figure 22, it is necessary to calculate the approximate storage capacity for each of the prospective sites, and evaluate it against the purpose for which the sand dam is constructed, which in all cases in the Hadjer Hadid catchment is in order to provide domestic water supply. Each of the sites need to calculate the reservoir volume making use of the formula derived in Section 4.1, and copied again here below.

$$V_S(eff) = 1.4\frac{n}{4}(D - 0.6 + \frac{0.1025}{n}) \times W \times L$$

In order to calculate the value D we need to take the deepest point in the sand reservoir, which means rather than taking the value at the proposed site, we need to use the deepest value recorded using the probing rod. Invariably, in light of our preference to build on ‘rocky outcrops’ and a ‘natural narrowing's' (see Section 5.5), the deepest point in the reservoir will fall at some point close behind the proposed dam location, but still well within the influence area of the dam. Thus D is calculated by summing the height of and dam and the depth of the deepest probe. Below in Table 13 the volume has been calculated, using porosity values calculated in Section 7.2.2 below:

*Table 13: Calculating the volume of water in the sand reservoir*

| Location | Max probe depth (m) | Height of dam from riverbed (m) | Maximum height, D (m) | Drainable Porosity, n (%) | Maximum reservoir width, W (m) | Total Throw-back, L (m) | Total Extractable Volume, V ($m^3$) |
|---|---|---|---|---|---|---|---|
| Am Haraz1 | 3.5m | 1.7m | 5.2m | 0.33% | 26m | 110m | 1600 $m^3$ |
| Am Haraz2 | 1.7m | 2.5m | 4.2m | 0.33% | 42m | 145m | 2800 $m^3$ |
| Boro Adjous | 1.4m | 1.1m | 2.5m | 0.33% | 52m | 161m | 2100 $m^3$ |
| Bredjine | 1.8m | 1.8m | 3.6m | 0.33% | 32m | 226m | 2800 $m^3$ |
| Faranga | 1.8m | 3.5m | 5.3m | 0.33% | 22m | 46m | 600 $m^3$ |
| Goz Met | 1.1m | 2.5m | 3.6m | 0.33% | 27m | 104m | 1100 $m^3$ |
| Hadjer Hadid | 1.7m | 2m | 3.7m | 0.33% | 74m | 293m | 8500 $m^3$ |
| Kokorguine | 1.6m | 2.5m | 4.1m | 0.33% | 37m | 145m | 2400 $m^3$ |
| Korrorak | 1.8m | 3m | 4.8m | 0.33% | 48m | 166m | 4200 $m^3$ |
| Labidé | 2.6m | 2.5m | 5.1m | 0.33% | 88m | 576m | 28200 $m^3$ |
| Louma Arab | 1.7m | 3.5m | 5.2m | 0.33% | 32m | 241m | 4400 $m^3$ |

This provides us with an estimation of the total volume of water stored behind the sand dam at each site. We now need to establish whether this is 'fit for the purpose'. In Hadjer Hadid, domestic water is the critical need which is the focus of this sand dam feasibility study (Section 1.3). Based on SPHERE standards, a minimum requirement for domestic water is 20 litres / person / day (Sphere Project, 2011), or 0.02 $m^3$. The dry season in Eastern Chad lasts (conservatively) ten months (304 days) of the year. Based on this information we can calculate what size population each sand dam site would be able to support for domestic water:

$$Population\ supported = \frac{V_S(eff)}{304 \times 0.02}$$

In addition to this, we estimate each household to have an average population of six people, typical of Eastern Chad, we are thus able to estimate the total number of households that each sand dam would support. These calculations are presented in Table 14 below, and compared in the final column with demographic data from Table 9

*Table 14: Total population that can be supported by each sand dam*

| Location | Total volume per annum ($m^3$) | Total volume per day during dry season ($m^3$) | Max. population supported (people) | Max population supported (households) | Total population of each village (households) |
|---|---|---|---|---|---|
| Am Haraz1 | 1600 $m^3$ | 5.3 | 267 | 44 | 60 |
| Am Haraz2 | 2800 $m^3$ | 9.0 | 452 | 75 | 60 |
| Boro Adjous | 2100 $m^3$ | 7.0 | 352 | 59 | 158 |
| Bredjine | 2800 $m^3$ | 9.1 | 455 | 76 | 70 |
| Faranga | 600 $m^3$ | 1.9 | 96 | 16 | 75 |
| Goz Met | 1100 $m^3$ | 3.5 | 177 | 29 | 145 |
| Hadjer Hadid | 8500 $m^3$ | 28.1 | 1405 | 234 | ≈1000 |
| Kokorguine | 2400 $m^3$ | 7.8 | 388 | 65 | 650 |
| Korrorak | 4200 $m^3$ | 13.7 | 683 | 114 | 48 |
| Labidé | 28200 $m^3$ | 92.6 | 4632 | 772 | 123 |
| Louma Arab | 4400 $m^3$ | 14.4 | 719 | 120 | 74 |

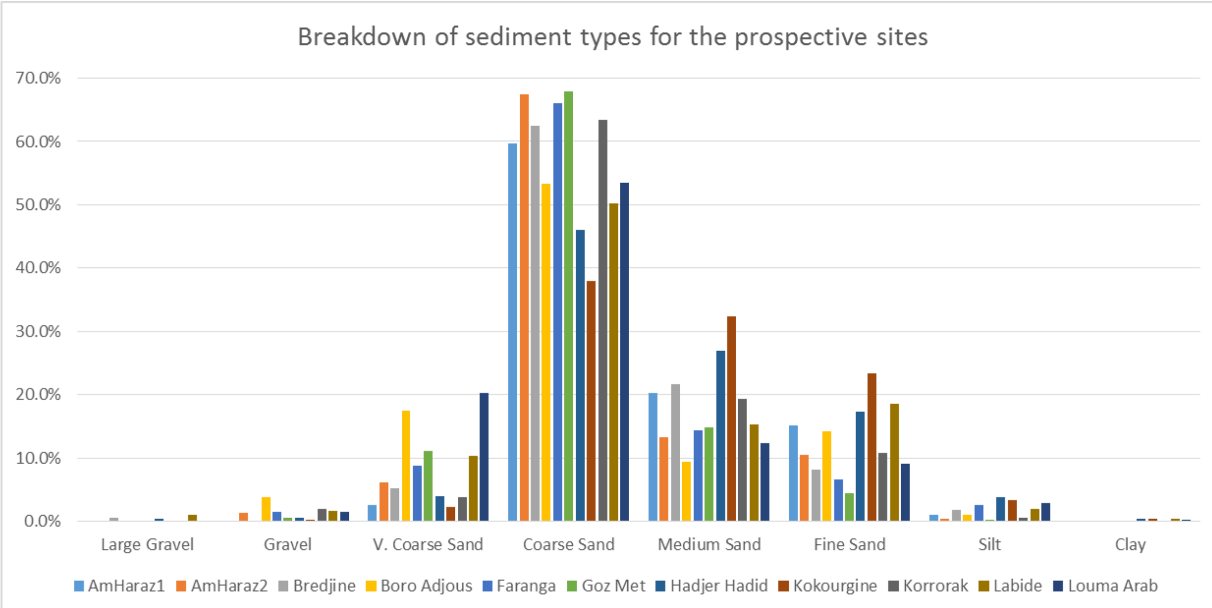
At five sites the sand dam storage capacity would be sufficiently large to provide domestic water supply to the whole population (AmHaraz2, Bredjine, Korrorak, Labidé, and Louma Arab). At all other locations the capacity would not be sufficient to provide water for the whole population, but would nonetheless be able to provide for a proportion of the population. This data is usefully compared to other types of technology, for example borehole and hand-pumps, which are able to provide water for 250-500 people in Eastern Chad. However, it would still be necessary for a fuller comparative cost-benefit analysis to be undertaken.

The one location that is likely not to provide sufficient water to be beneficial is Faranga (water for 16 households), though Goz met also has only a relatively small impact (water for 39 households). This will be further explored in the Affordability Analysis (Section 7.3), but here it suffices to conclude that all but one of the locations will provide a sufficient water supply to meet its purpose, and thus they meet criteria 2Ai.

### 7.2.2. Sediment accumulation

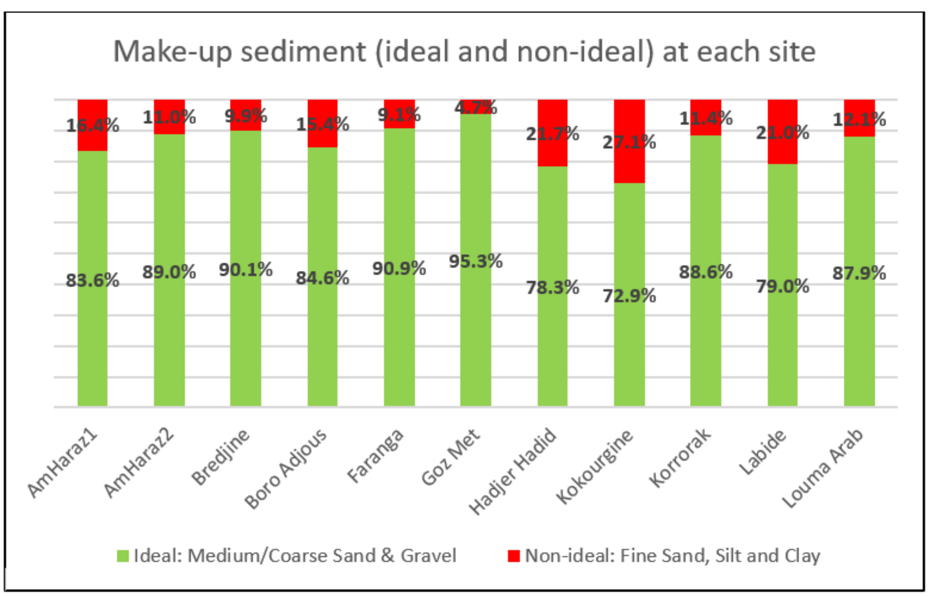
We need to apply the conditions from Figure 22, 2B, in order to establish whether the sediment at each site is suitable for sand dams. The sediment analysis undertaken for each site, listed in Table 10, is expressed graphically below in Figure 42.

*Figure 42: Breakdown of sediment types for the prospective sites*



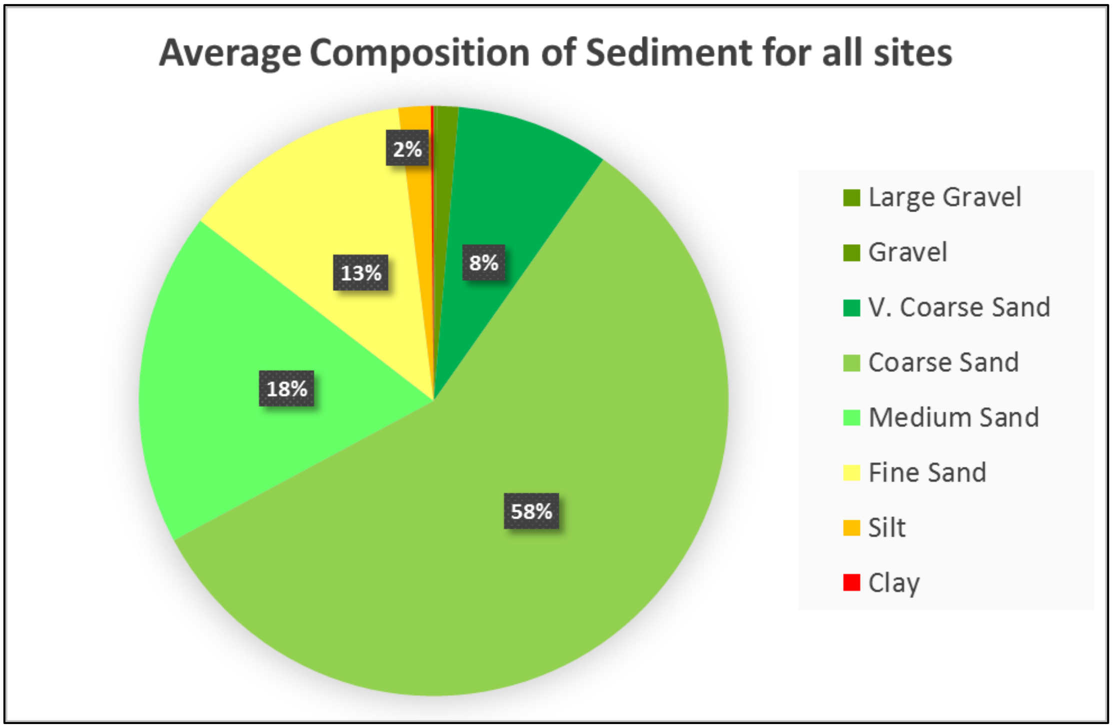

Condition 2Bi in the feasibility framework requires that there be sand naturally present at each site, and that the sand should be of minimum grain size 0.2mm. On the graph in Figure 42 this requires the sand present to be medium sand or coarser. It can be seen that the largest single classification of sand present at each site was coarse sand. By restrictively classifying the sand as their 'ideal' (>0.2mm, i.e. medium sand or larger) and 'non-ideal' (<0.2mm, i.e. fine sand or smaller), we are able to divide the sediment into two categories, as demonstrated in Figure 43.

*Figure 43: Categorisation of sediment into 'ideal' and 'non-ideal' for each site*



It can be seen that a high proportion of appropriate sediment can be found at each of the sites, and only Hadjer Hadid (21.7%), Kokorguine (27.1%) and Labidé (21%) have a proportion of non-ideal sediments greater than 20%. Based on the sediment transport principles set forth in Section 4.3, this represents a favourable sediment make-up, and the condition has been satisfied. The 'catchment' summary (average of all the sites) is encapsulated in the pie chart in Figure 44.

*Figure 44: Average sediment classification for all sites in Hadjer Hadid catchment*




The drainable porosity of the sand reservoir at each location can be calculated by using Figure 17, which requires us to input the median grain size, which in all eleven cases here is coarse sand, i.e. a grain size of 0.5mm – 1mm. This yields an approximate porosity of 0.33%, which will be the value used in all further calculations in this feasibility study, most especially in calculating the reservoir volume in Section 7.2.1.

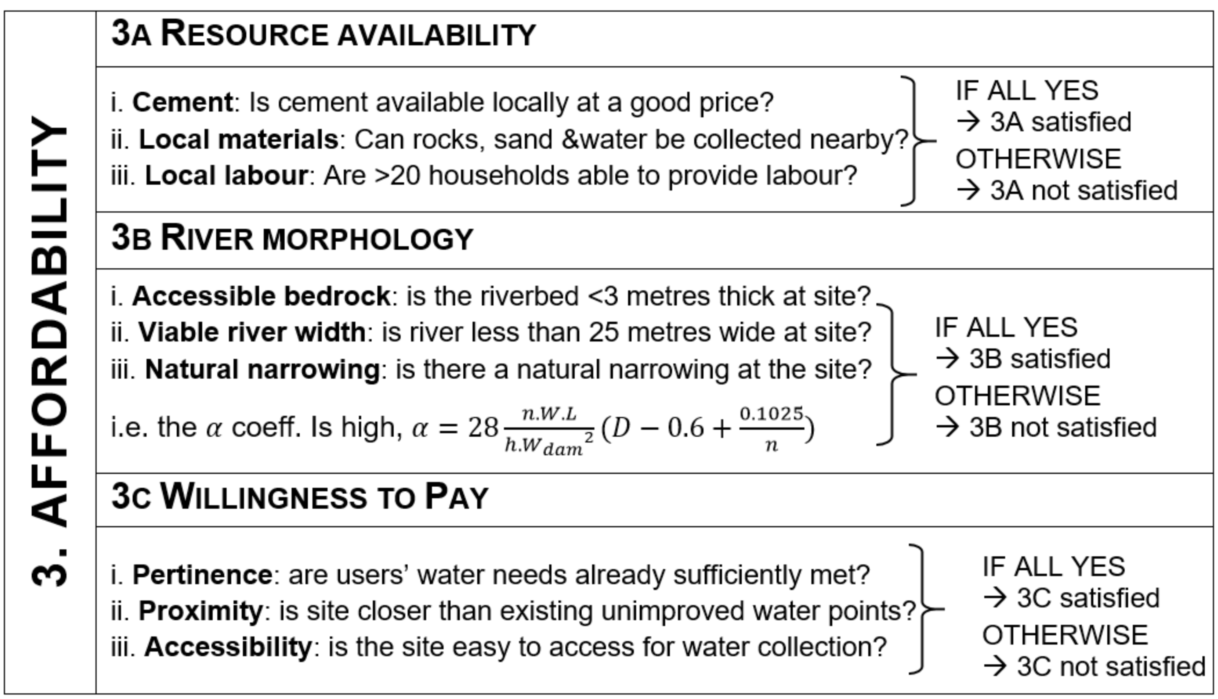
For the sake of fullness, we will briefly overview condition 3Bii, even though this is not required in light of the above results meeting condition 3Bi. We are required to establish a 'both, and' condition: that the catchment mean slope is greater than 2% and that the riverbed slope immediately upstream of the site is between 1% and 5%. It can be seen from Table 15 that this condition is satisfied at every site with respect to catchment mean slope, and all but two sites with respect to the riverbed slope upstream. Only Hadjer Hadid (0.9%) and Labidé (0.8%) failed to meet the 1% threshold, but this is likely within the margin of human calculation error, and also in light of condition 2Bi being satisfied, we can be fairly sure that sediment characteristics will be favourable there also.

*Table 15: Catchment mean slope and riverbed slope for each site*

| Location | Riverbed slope upstream (%) | Catchment mean slope (%) |
|---|---|---|
| Am Haraz1 | 1.3% | 6.3% |
| Am Haraz2 | 2.1% | 8.7% |
| Boro Adjous | 1.2% | 3.9% |
| Bredjine | 1.3% | 7.5% |
| Faranga | 1.5% | 5.1% |
| Goz Met | 2.8% | 3.4% |
| Hadjer Hadid | 0.9% | 4.3% |
| Kokorguine | 1.7% | 5.2% |
| Korrorak | 2.1% | 7.9% |
| Labidé | 0.8% | 3.8% |
| Louma Arab | 1.5% | 3.8% |

## 7.3. AFFORDABILITY

We will now apply the feasibility framework in Figure 24 (copied again below) to evaluate the storage capacity criteria for the Hadjer Hadid catchment, by considering first the reservoir volume (2A) and secondly the Sediment Accumulation (2B).



### 7.3.1. Resource availability

Here we need to establish whether there is a sufficient supply of resources to render the sand dam affordable, in particularly with respect to cement (3Ai), local materials (3Aii), and local labour (3Aiii). Hadjer Hadid town has a very reliable supply of cement available in the market place, sourced both from Ndjamena (the capital of Chad) and alternatively from Sudan across the border. It is thus on this occasion straightforward to satisfy condition 3Ai for all our locations.

Likewise, the landscape of Hadjer Hadid catchment is such that there is ample supply of rocks across the whole region, and in particular for each site there are rocks readily available nearby for construction. Thus 3Aii is also satisfied for all our sites.

Finally, the requirement to have sufficient local labour to undertake sand dam construction is calculated by considering the results of Section 7.2.1, where we calculated the capacity of each sand dam and the number of households that it would be able to support. Our threshold requirement is that there be a minimum of twenty households to provide labour for construction. Apart from Faranga, all sites would provide domestic water for in excess of twenty households. However, Faranga only have storage capacity to provide year round domestic water for 16 households (Table 14), which will be insufficient.

As such all locations are considered to meet criteria 3Aiii except for Faranga which must be discounted on these grounds.

### 7.3.2. River morphology

It can be seen from Table 11 that all eleven sites have bedrock which is less than three metres below the riverbed and also have a width of less than 25 metres. Thus conditions 3Bi and 3Bii are met by all sites.

Now we must undertake an analysis of the ‘quality of the narrows’ (condition 3Biii) to identify which locations have the best morphology for a natural narrowing at the proposed dam site. To do this we must calculate the $\alpha$ coefficient for each site, which has the following formula:

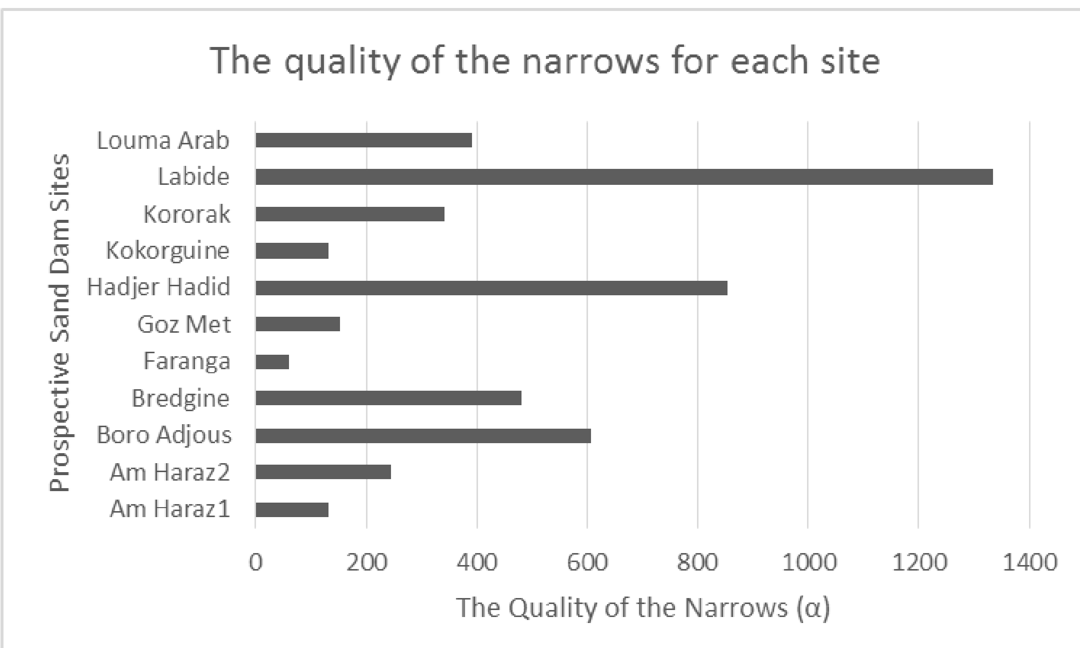
$$\alpha = 28\frac{n.W.L}{h.{W_{dam}}^2}(D - 0.6 + \frac{0.1025}{n})$$

This calculation is undertaken using n = 0.33% for porosity. A summary is provided in Table 16 and it is expressed graphically in Figure 45. This provides us with tools of comparison, where the greater the alpha coefficient, the more cost effectiveness the prospective site is.

*Table 16: Calculating the 'quality of the narrows' for each site*

| **Location** | Maximum height, D (m) | Drainable Porosity, n (%) | Maximum reservoir width, W (m) | Total Throw-back, L (m) | With of river at site (m) | Height of dam at site (m) | $\alpha$ |
|---|---|---|---|---|---|---|---|
| Am Haraz1 | 5.2 | 0.33 | 26 | 110 | 24 | 1.7 | 133 |
| Am Haraz2 | 4.2 | 0.33 | 42 | 145 | 19 | 2.5 | 244 |
| Boro Adjous | 2.5 | 0.33 | 52 | 161 | 16 | 1.1 | 607 |
| Bredjine | 3.6 | 0.33 | 32 | 226 | 16 | 1.8 | 480 |
| Faranga | 5.3 | 0.33 | 22 | 46 | 15 | 3.5 | 59 |
| Goz Met | 3.6 | 0.33 | 27 | 104 | 15 | 2.5 | 153 |
| Hadjer Hadid | 3.7 | 0.33 | 74 | 293 | 20 | 2.0 | 854 |
| Kokorguine | 4.1 | 0.33 | 37 | 145 | 24 | 2.5 | 131 |
| Korrorak | 4.8 | 0.33 | 48 | 166 | 18 | 3.0 | 342 |
| Labidé | 5.1 | 0.33 | 88 | 576 | 26 | 2.5 | 1333 |
| Louma Arab | 5.2 | 0.33 | 32 | 241 | 16 | 3.5 | 391 |

*Figure 45: The quality of the narrows for each site*




It can be seen here that in particular Faranga, Kokorguine, Goz Met and Am Haraz1 are particularly low scoring, whereas the others are more favourable. We can return to this tool as a means of categorising prospective sites in the summary Section 7.4.

### 7.3.3. Willingness to pay

There are some technical and environmental factors which are easily measurable which help us to establish the community's willingness to pay. However, this is clearly only a precursor to a fuller community engagement survey which will need to be undertaken, and which is outlined in Section 8.2. The first condition, 3Ci, is to ensure that the sand dam is pertinent – i.e. that it is address a water need, and that the needs of the users are not already fully met by another solution. It can be seen in Table 9 that a number of the sites have villages which already have a borehole mounted with a handpump. Though many of these are broken-down, they are nonetheless valuable assets. However, the population of each community is such that a single borehole proves inadequate to supply their water needs, and as such in all cases condition 3Ci is satisfied since their remains a chronic shortage of water supply for each community, and there is no evidence at any of the sites to suppose that a sand dam would be superfluous to the local water needs.

Furthermore, the selection of the sites was carefully considered to ensure that it was as close as possible to the villages, and in every case it is either closer than the existing unimproved water source, or in a number of cases it is sited in the same riverbed as it currently being used for water extraction. Thus all locations satisfy condition 3Cii.

The final condition, 3Ciii, relates to ease of access to the sand dam sites. All the locations were relatively easy to access with the exception of Faranga, which was located in a steep gorge which could only be entered with considerable difficulty. A panoramic photo of the Faranga location is provided in Figure 46 to illustrate this difficulty.

*Figure 46: Panorama of with Faranga site with difficult access*

Thus with regard to willingness to pay, conditions 3Ci and 3Cii are satisfied by all sites. Condition 3Ciii is satisfied by all sites except for Faranga.

## 7.4. Summary

Below is a summary of the feasibility study, with green boxes representing that the condition was met, red boxes representing that it was not met, and orange boxes used to represent a concern, but one which is not considered critical. This is presented in Table 17:

*Table 17: Summary of feasibility study for Hadjer Hadid catchment*

| | | | Am Haraz1 | Am Haraz2 | Boro Adjous | Bredjine | Faranga | Goz Met | Hadjer Hadid | Kokorguine | Korrorak | Labidé | Louma Arab |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 WATER SUPPLY | 1A | **Impermeable Bedrock** | | | | | | | | | | | |
| | | i. Appropriate geology | | | | | | | | | | | |
| | | ii. Factures or Faults | | | | | | | | | | | |
| | | iii. Scoop holes | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| | 1B | **Appropriate Rainfall** | | | | | | | | | | | |
| | | i. Sufficient Rainfall | | | | | | | | | | | |
| | | ii. Environmental | | | | | | | | | | | |
| 2 STORAGE CAPACITY | 2A | **Reservoir Volume** | | | | | | | | | | | |
| | | i. Sufficient water | | | | | | | | | | | |
| | 2B | **Sediment Accumulation** | | | | | | | | | | | |
| | | i. Sand naturally present | | | | | | | | | | | |
| | | ii. Catchment slope | | | | | | | | | | | |
| | | iii. Riverbed slope | | | | | | | | | | | |
| 3 AFFORDABILITY | 3A | **Resource Availability** | | | | | | | | | | | |
| | | i. Cement | | | | | | | | | | | |
| | | ii. Local Materials | | | | | | | | | | | |
| | | iii. Local Labour | | | | | | | | | | | |
| | 3B | **River Morphology** | | | | | | | | | | | |
| | | i. Accessible Bedrock | | | | | | | | | | | |
| | | ii. Viable River Width | | | | | | | | | | | |
| | | iii. Natural Narrowing | See Summary Section Error: Reference source not found | | | | | | | | | | |
| | 3C | **Willingness to Pay** | | | | | | | | | | | |
| | | i. Pertinence | | | | | | | | | | | |
| | | ii. Proximity | | | | | | | | | | | |
| | | iii. Accessibility | | | | | | | | | | | |

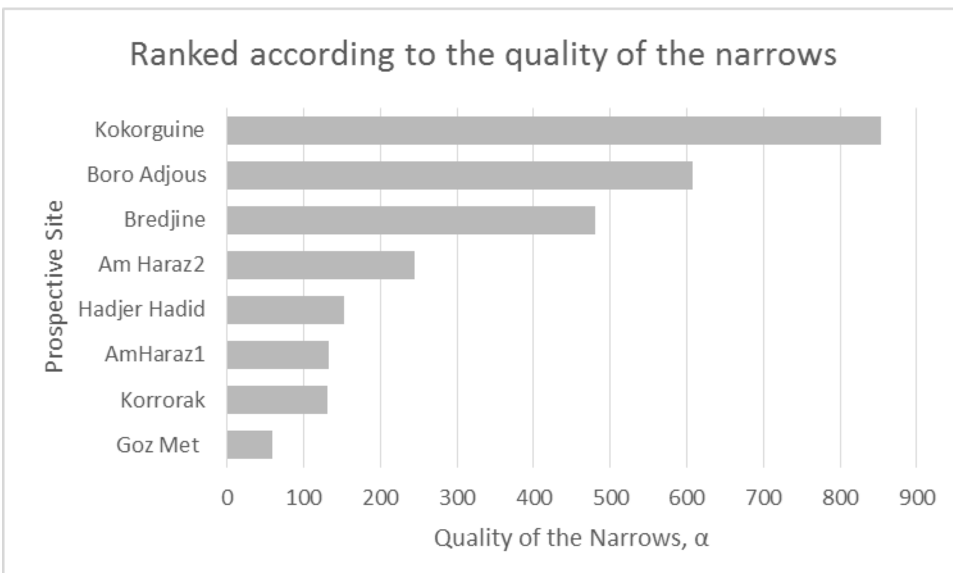
As can be seen the vast majority of the parameters are returned positive on almost every occasion, and there are two reasons for this. Firstly, a lot of caution was already exercised in selecting these eleven sites, whereby many conditions were already satisfied on account of a good selection process in the first place. For example sites were pre-selected which did have sand present (condition 2Bi) and which we less than 25 metre in width (condition 3Bii). Secondly, it requires only one occasion of a condition not being satisfied to discount the location in its entirety. As such even with only a few negative results above, we are required to discount three locations from being feasible for sand dams:

- **Faranga:** did not meet condition 2Ai/3Aiii and 3Ciii: too few users are supported
- **Labidé**: did not meet condition 1Aii: it is located on a fracture/fault
- **Louma Arab:** did not meet condition 2Bii: too great negative environmental impact

We are thus left with eight sites which from a technical feasibility point of view can be considered eligible. There are of course other factors that need to be considered (Section 8.2), but nonetheless we have successfully applied the feasibility framework developed in this paper to the context of Hadjer Hadid in eastern Chad.

Finally, we will return to the 'quality of the narrows' parameter as a means of ranking these sand dams in terms of their technical favourability. Once the above three negative sites have been discounted, the remaining eight locations are ranked in Figure 47, providing a general cost-benefit coefficient, and some guidance as to which sites will be most cost-effective.

*Figure 47: Ranking sand dam sites according to the quality of the narrows:*




Thus we can see that Kokorguine is the most favourable site according to this parameter, and Goz Met is by far the least favourable. This method of ranking can provide guidance to practitioners in making recommendations for which sites to select. Furthermore, where there are hundreds of prospective sites, it can be used as a means of discounting a significant number and only constructing sand dams where they will be most effective.

# 8. CONCLUSION

## 8.1. REFLECTIONS ON RESULTS

The above results and analysis are only as good as the underlying data which they make use of, and it is appropriate to reflect on its reliability, and its impact on the feasibility study. There are a number of limitations in the data collection and analysis process which should be acknowledged:

- Undertaking this research with only eleven data points is restricting, and it is unlikely that we can extrapolate from them to make conclusive recommendations about other locations both within the Hadjer Hadid catchment and beyond. However, the time limitations of this research meant that it was not possible to extend the scope more broadly.
- Additionally, the timing of the field visits was unfortunate. These were undertaken in June, which is typically the final month of dry reason prior to rains coming in July. However, this year there were significant early rains which meant that analysis of water levels in the riverbeds would have returned spurious results and was therefore not undertaken. Ideally we would have liked to be able to know the water levels of the riverbed at the end of dry season, as well as the location of scoop holes, some of which had already been covered over by the early rains.
- There was a number of simplifications which undermined the quality of the results. In particular the rainfall data for Hadjer Hadid was not available and therefore interpolation was required to estimate this, and rates of evapotranspiration had to be estimated in a rudimentary way. Furthermore, the instruments calculating the slopes of the riverbeds were not as accurate as would have been hoped.
- It was hard to estimate demographic data, and even harder to forecast how this will change in the future. Ideally, we should project the population of villages into the future and use these as our estimates of water demand. However, the region of Hadjer Hadid has experienced a decade of demographic change, with thousands of Darfur refugees relocating there, and many other migrating to cities or overseas. As such that it was not deemed sensible to estimate how population would change in the future and so current figures were relied upon.
- Most significantly of all, restricting the research to merely the technical factors of feasibility is a major shortfall, a fuller discussion of which is presented in Section 8.2 below. At best this research is incomplete, since it is impossible to establish the feasibility of a proposal without engaging thoroughly with the stakeholders and users most impacted by it.

Nonetheless, the data was sufficient to apply the feasibility framework developed in Chapters 3, 4 and 5 to the Hadjer Hadid catchment. In this respect the data has been useful as a means of demonstrating how the framework should be applied to an actual context, and it is hoped that other practitioners will be able to use these results as a model for their own feasibility assessments.

## 8.2. SOCIO-ECONOMIC FACTORS

Technical ('hard') feasibility, the topic of this research, must be undertaken hand in hand with assessment of the socio-economic and political ('soft') landscape into which sand dams are being implemented. The field visit to Haouish was a clear reminder of the importance of this, where two sand dams (Haouish town and Haouish Zaribe) had been constructed well, but their failure was the result of the local communities not having a felt need for them and so not taking responsibility to maintain them. The author originally undertook significant data collection regarding socio-economic and political factors, in addition to the technical factors mentioned in this paper. However, because of length restrictions it was not included in this paper; however; however it is hoped that a second paper will apply this data look into feasibility for sand dams in Chad from this 'soft' side. Notwithstanding this, here a precursory reference some socio-economic factors is included, in order to emphasise that these need to be complemented with the technical feasibility:

1. **Social feasibility**: the success of the sand dam is contingent on the civil society structures that exist to maintain it, and as such it is important that there is cohesive local community that takes ownership of the sand dam (Ertsen et al., 2005). Where communities are disparate or struggling with internal or tribal tensions, sand dams will likely not be maintained in a sustainable manner (Stern & Stern, 2011:2). As such it is appropriate to review what community structures and self-help groups exist and to make this the starting point of any consideration of feasibility.

2. **Political feasibility**: it is important to operate within the laws and protocols of the government. This is particularly relevant for contexts where sand dams have not yet been introduced, since there will often be policies and guidelines for integrated water resource management (IWRM) in law which are required to be followed. As such, it is often necessary to engage local government and relevant ministries, and through advocacy and education promote the concept of sand dams. Sand dams are unlikely to experience widespread success unless there is the political will to enable them (Stern & Stern, 2011:5. Finally, ownership is an important concept, both in terms of determining who owns the land on which a sand dam is constructed, but also whose responsibility the sand dam is long-term to oversee and maintain (Munyao et al., 2004:11).

3. **Economic feasibility:** in rural areas communities often have very limited resources to contribute to maintain their water resources, and often this results in breakdown and a return to traditional unimproved sources for water collection. It is essential to evaluate the economic enabling environment of the region to determine whether sand dams will be sustainable. Munyao et al. (2004:13) describe a situation where multiple villages together take on responsibility for a sand dam

in Kenya since there is insufficient capacity in any one village to manage the sand dam. An analysis of the overhead and running costs of the sand dam needs to be assessed and evaluated against the economic burden that this will place on the users, and whether this is feasible.

A sober reminder of the importance of these ‘soft’ issues can be found in Nissen-Petersen’s (2006) reference to an evaluation which registered that only 5% of sand dams in Kitui region constructed over the last 40 years are still operational. May we take notice and look seriously at sustainability.

## 8.3. RECOMMENDATIONS

The whole of this research has been working towards answering research question 3: “To what extent does Eastern Chad provide an appropriate context for sand dams?” Though we admit that our data does not allow for a conclusive answer to this question, significant progress has been made towards it. The third research question has been ‘being answered’ throughout the whole body of this research, but now it is appropriate to offer some recommendations about a way forward for those looking at sand dam feasibility for eastern Chad:

- **Sand dams should be piloted in Eastern Chad**. It is appropriate for sand dams to be constructed in eastern Chad. The results of this paper, whilst incomplete for not having considered non-technical factors, nonetheless presents sufficiently favourable results for it to be appropriate to trial sand dams. This is particularly pertinent in light of the difficulties that the region has had with meeting its water needs through existing technologies, which is primarily open wells and handpump-mounted deep boreholes. It is hoped that organisations on the ground, in partnership with the government, will make steps towards implementing this new technology.
- **Sand dams should not be implemented at any site**. It is obvious from these results that potentially favourable sites (as all these eleven were considered to be at first inspection) do not necessarily warrant sand dam construction. Rather, it is necessary to ensure thorough analysis of all proposed sites in order to assess whether the conditions are suitable, and as sand dams are introduced to eastern Chad this should be emphasised as the way forward.
- **Further research is required:** this research needs to be followed up with a companion paper to consider the socio-economic factors related to sand dams, and assess the extent to which there exists an enabling environment for sand dam implementation in eastern Chad. Additionally, upon completion of an initial trial of sand dams in eastern Chad, a review should be undertaken prior to them being implemented more widely to establish whether they are accomplishing their objectives in meeting the water needs of communities in eastern Chad.

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# 10. APPENDICES

## 10.1 APPENDIX: RAINFALL DATA

Using gridded data from Data Source: Schneider et al. (2015) for region 13.25N 21.75E (applicable for the Hadjer Hadid catchment area), produces the following raw data:

*Table 18: Annual total precipitation data for years 1901 to 2013*

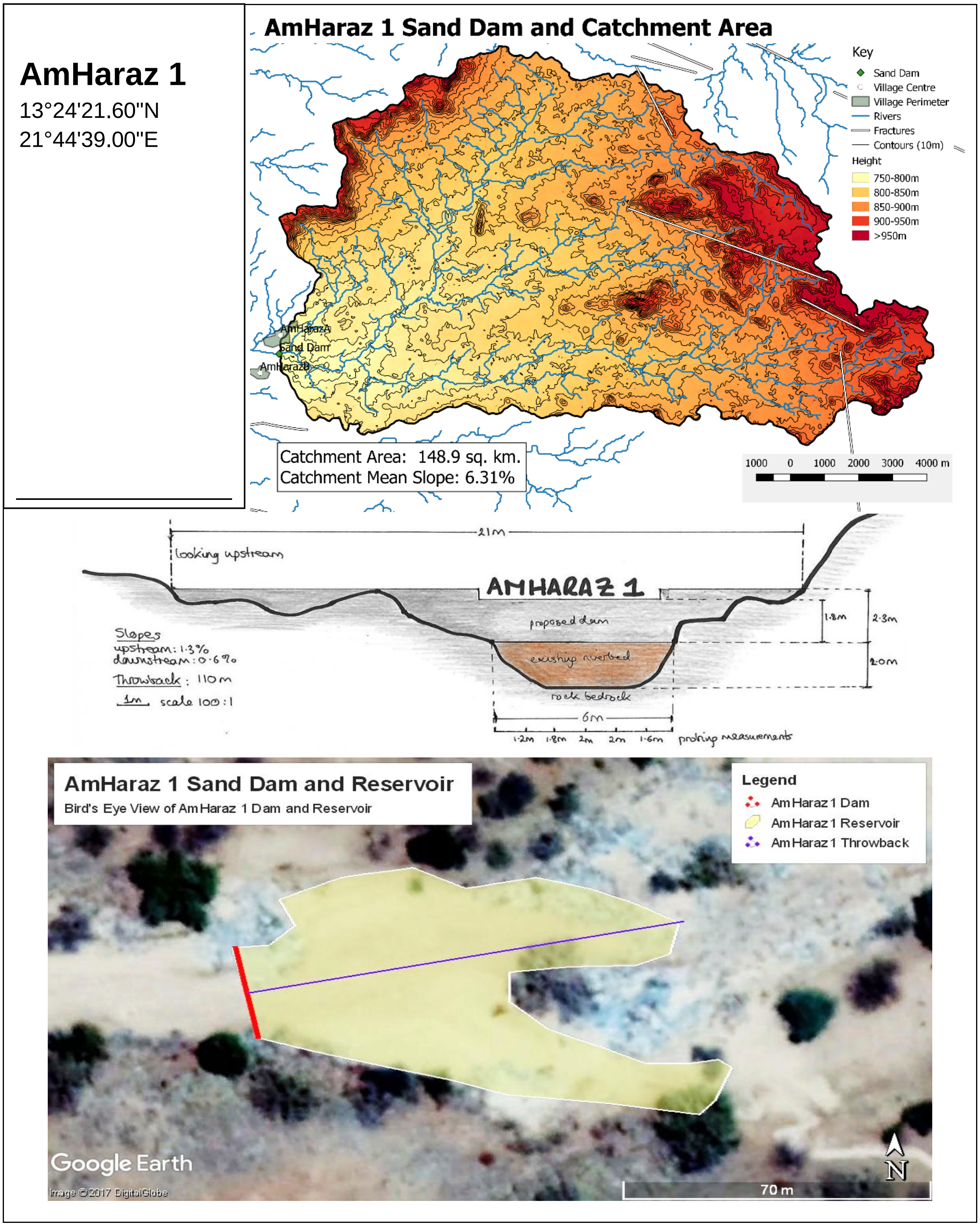
| Year | Annual Rainfall |
|---|---|
| 1901 | 435mm |
| 1902 | 490mm |
| 1903 | 374mm |
| 1904 | 317mm |
| 1905 | 451mm |
| 1906 | 560mm |
| 1907 | 503mm |
| 1908 | 557mm |
| 1909 | 599mm |
| 1910 | 509mm |
| 1911 | 469mm |
| 1912 | 516mm |
| 1913 | 283mm |
| 1914 | 579mm |
| 1915 | 511mm |
| 1916 | 526mm |
| 1917 | 460mm |
| 1918 | 541mm |
| 1919 | 567mm |
| 1920 | 691mm |
| 1921 | 468mm |
| 1922 | 852mm |
| 1923 | 659mm |
| 1924 | 687mm |
| 1925 | 483mm |
| 1926 | 450mm |
| 1927 | 609mm |
| 1929 | 547mm |
| 1930 | 671mm |
| 1931 | 546mm |
| 1932 | 495mm |
| 1933 | 562mm |
| 1934 | 739mm |
| 1935 | 558mm |
| 1936 | 632mm |
| 1937 | 618mm |
| 1938 | 633mm |
| 1939 | 537mm |
| 1940 | 429mm |
| 1941 | 506mm |
| 1942 | 494mm |
| 1943 | 550mm |
| 1944 | 531mm |
| 1945 | 518mm |
| 1946 | 909mm |
| 1947 | 618mm |
| 1948 | 483mm |
| 1949 | 458mm |
| 1950 | 706mm |
| 1951 | 543mm |
| 1952 | 549mm |
| 1953 | 758mm |
| 1954 | 654mm |
| 1955 | 605mm |
| 1957 | 747mm |
| 1958 | 595mm |
| 1959 | 526mm |
| 1960 | 566mm |
| 1961 | 622mm |
| 1962 | 648mm |
| 1963 | 643mm |
| 1964 | 697mm |
| 1965 | 451mm |
| 1966 | 625mm |
| 1967 | 557mm |
| 1968 | 552mm |
| 1969 | 557mm |
| 1970 | 490mm |
| 1971 | 390mm |
| 1972 | 342mm |
| 1973 | 360mm |
| 1974 | 427mm |
| 1975 | 495mm |
| 1976 | 430mm |
| 1977 | 444mm |
| 1978 | 499mm |
| 1979 | 475mm |
| 1980 | 465mm |
| 1981 | 426mm |
| 1982 | 341mm |
| 1983 | 331mm |
| 1984 | 220mm |
| 1986 | 362mm |
| 1987 | 261mm |
| 1988 | 660mm |
| 1989 | 511mm |
| 1990 | 300mm |
| 1991 | 500mm |
| 1992 | 477mm |
| 1993 | 364mm |
| 1994 | 664mm |
| 1995 | 519mm |
| 1996 | 384mm |
| 1997 | 514mm |
| 1998 | 545mm |
| 1999 | 587mm |
| 2000 | 332mm |
| 2001 | 499mm |
| 2002 | 441mm |
| 2003 | 651mm |
| 2004 | 434mm |
| 2005 | 701mm |
| 2006 | 568mm |
| 2007 | 529mm |
| 2008 | 362mm |
| 2009 | 447mm |
| 2010 | 569mm |
| 2011 | 507mm |
| 2012 | 671mm |
| 2013 | 504mm |

*Figure 48: Rainfall mean and standard deviation for Hadjer Hadid region*

| | Historic (1901-2013) | Recent (1981-2013) |
|---|---|---|
| **Rainfall Mean** | 528mm | 474mm |
| **Rainfall Standard Deviation** | 121mm | 124mm |

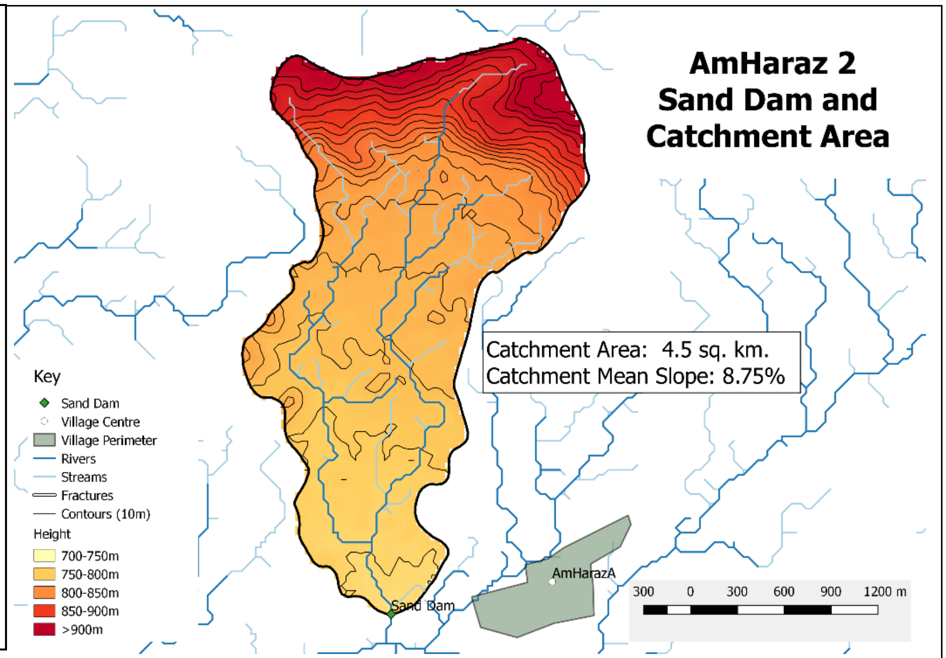
## 10.2 APPENDIX: DATA PRESENTATION

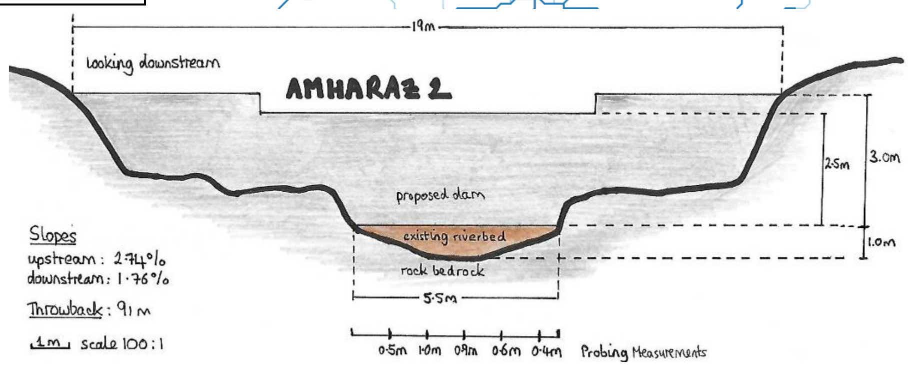
*Figure 49: Presentation of data for the 11 proposed sand dam sites*

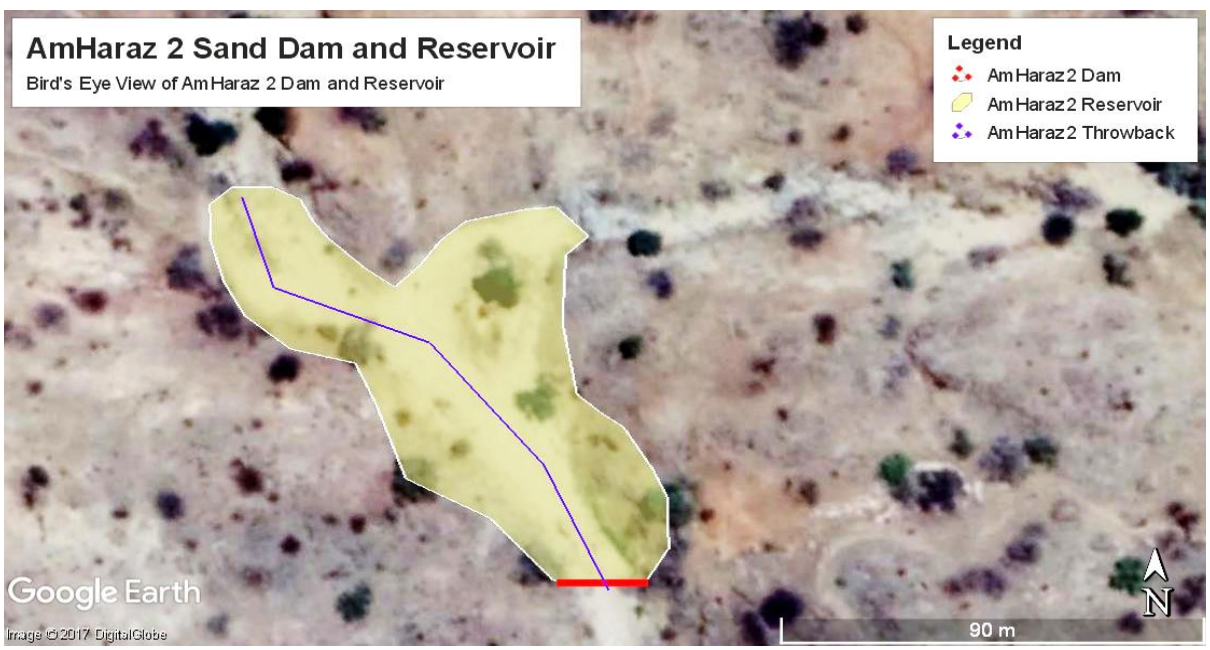


## AmHaraz 2

13°24'33.00"N
21°44'6.12"E

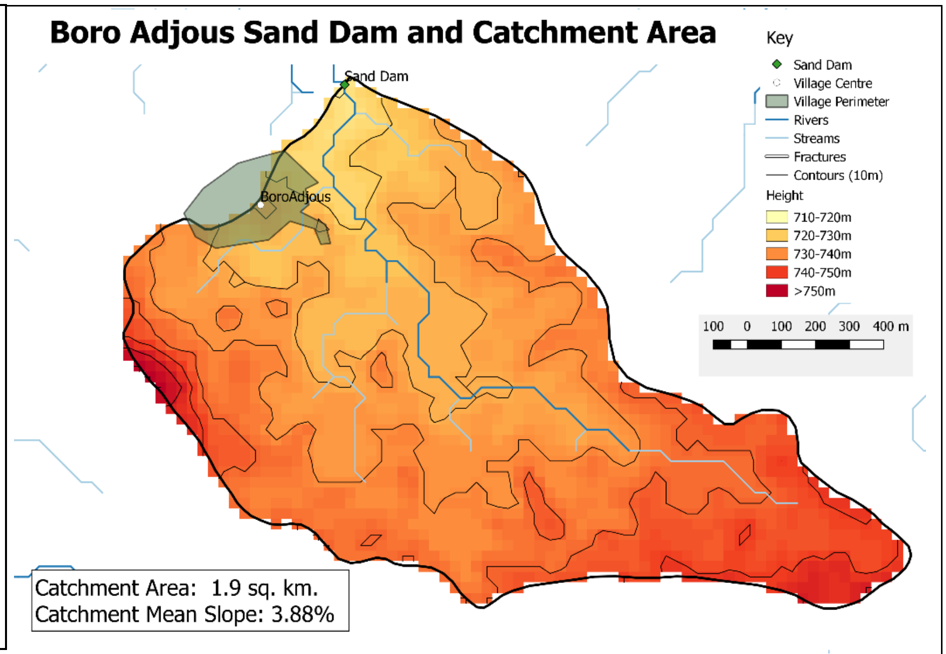


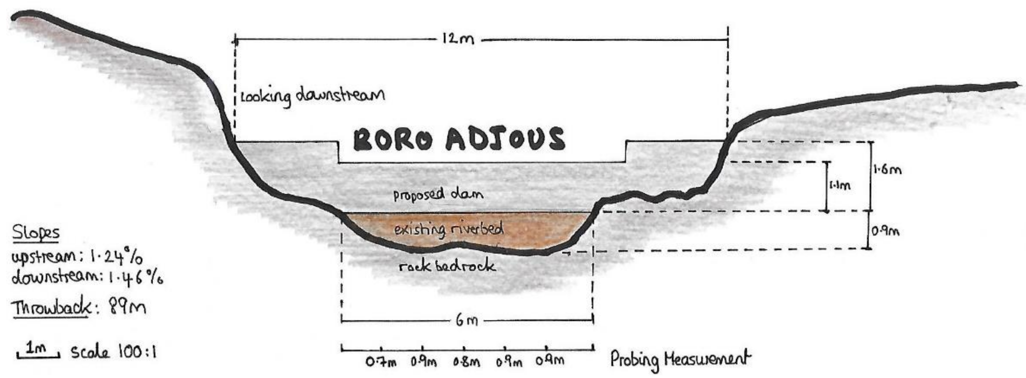



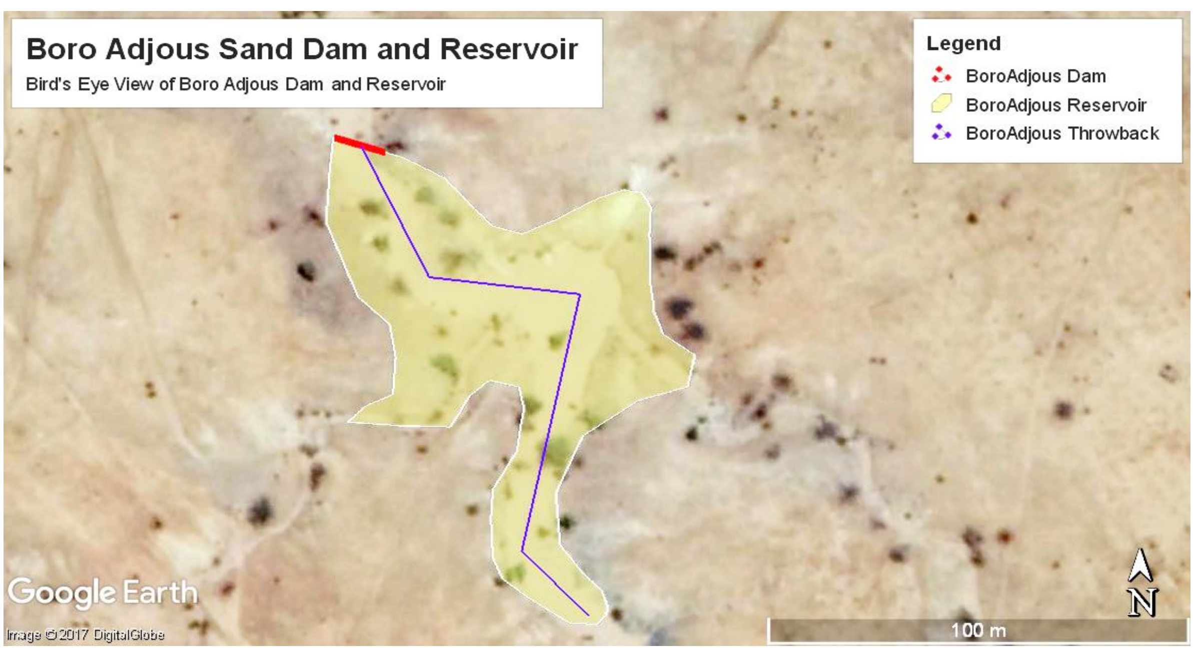



# Boro Adjous

13°22'41.46"N
21°41'38.28"E

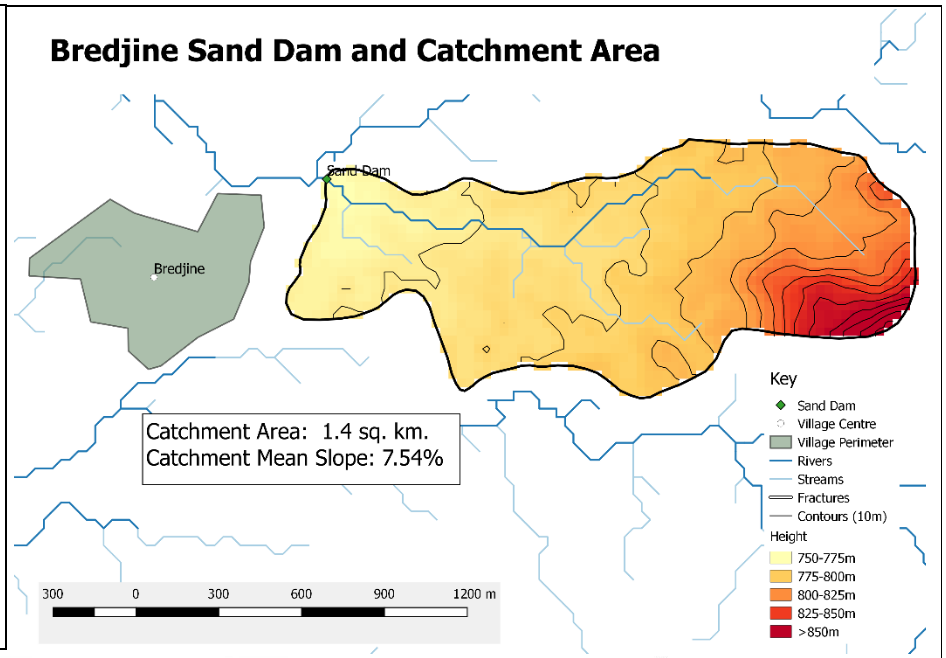


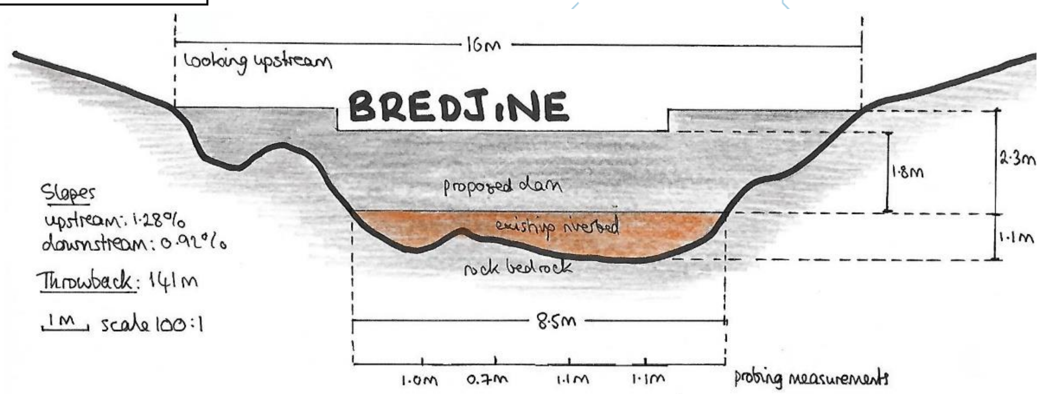



# Bredjine

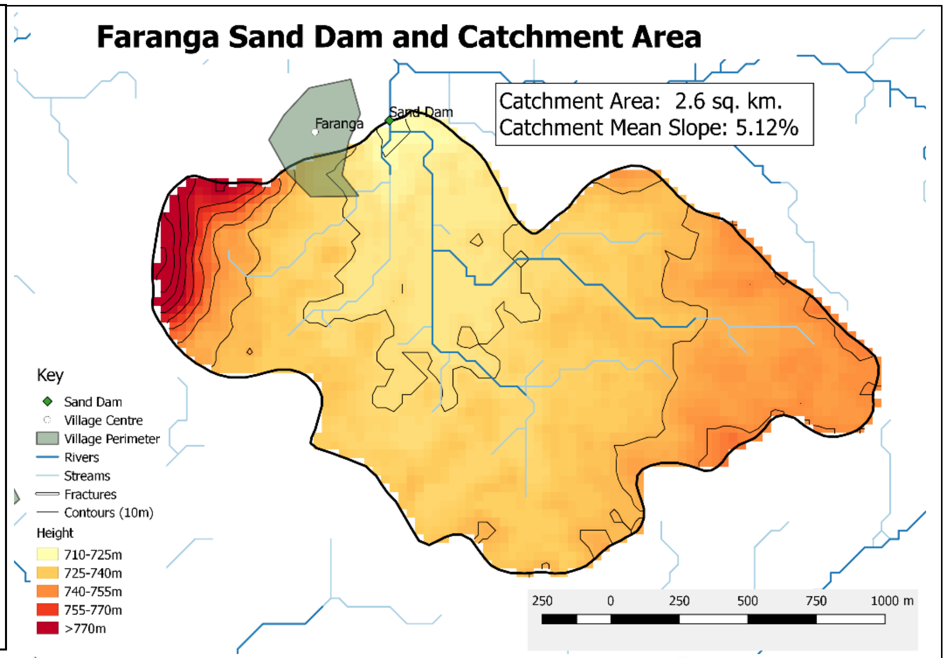
13°29'15.96"N
21°43'55.62"E

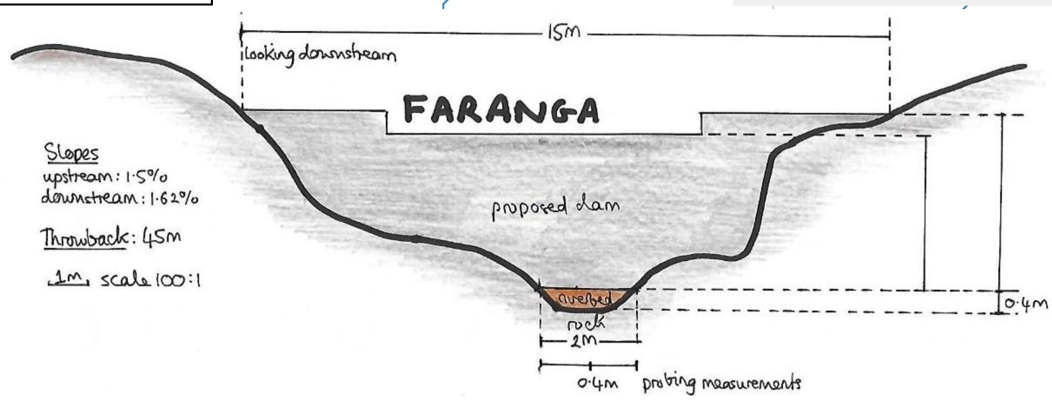


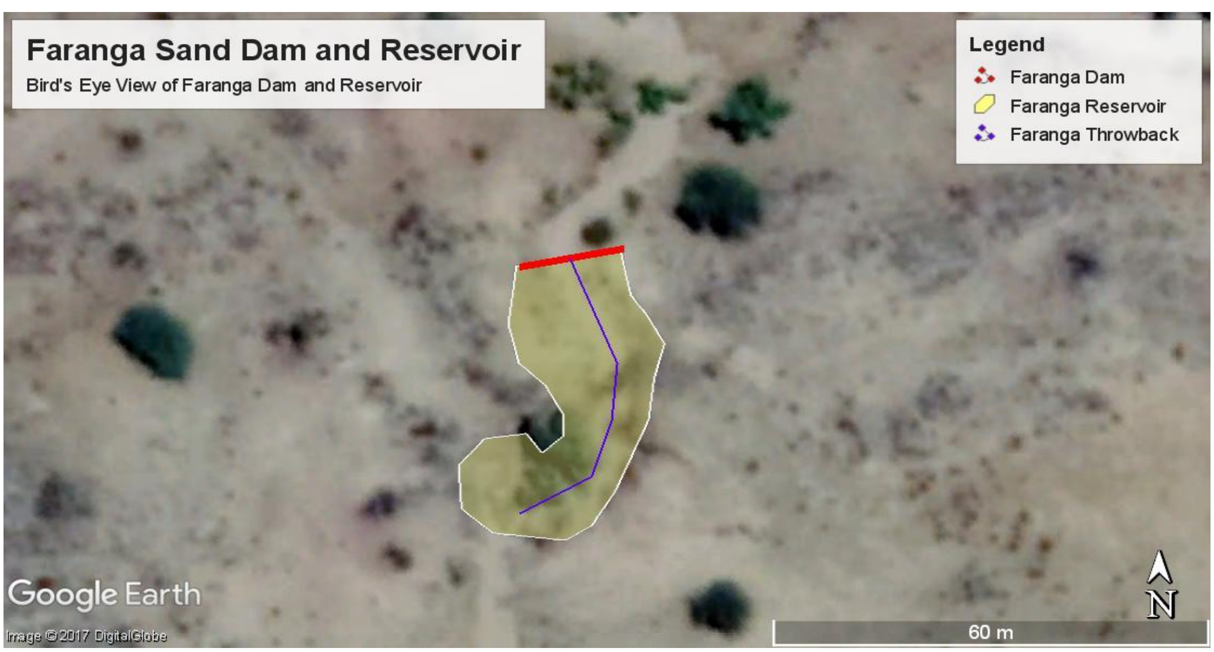




# Faranga

13°27'33.90"N
21°41'15.42"E

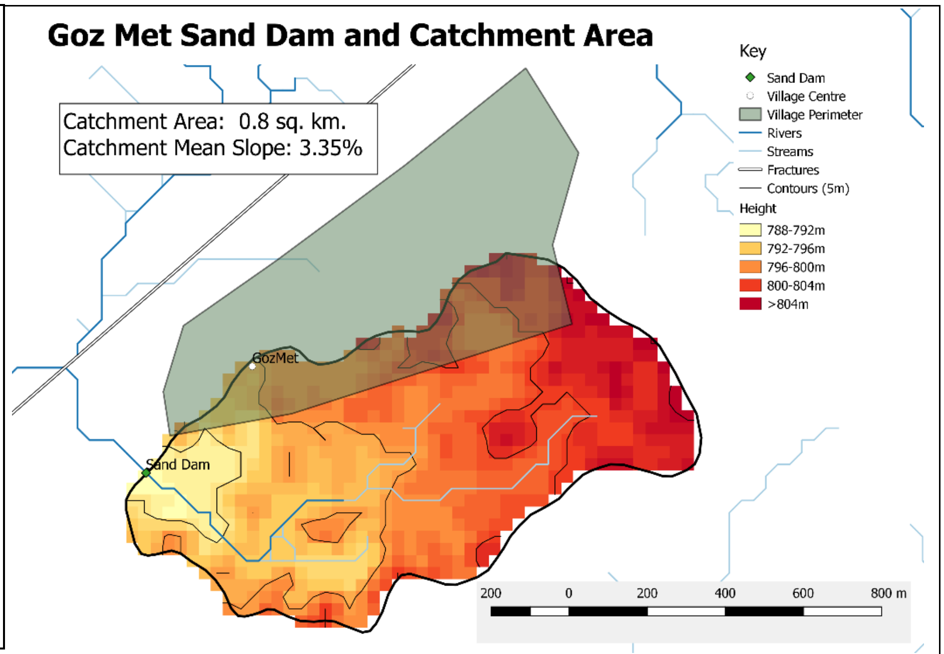


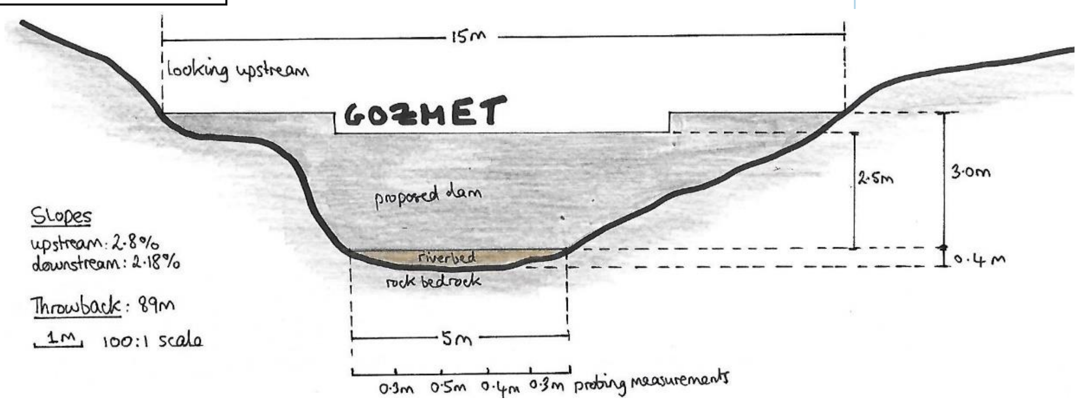



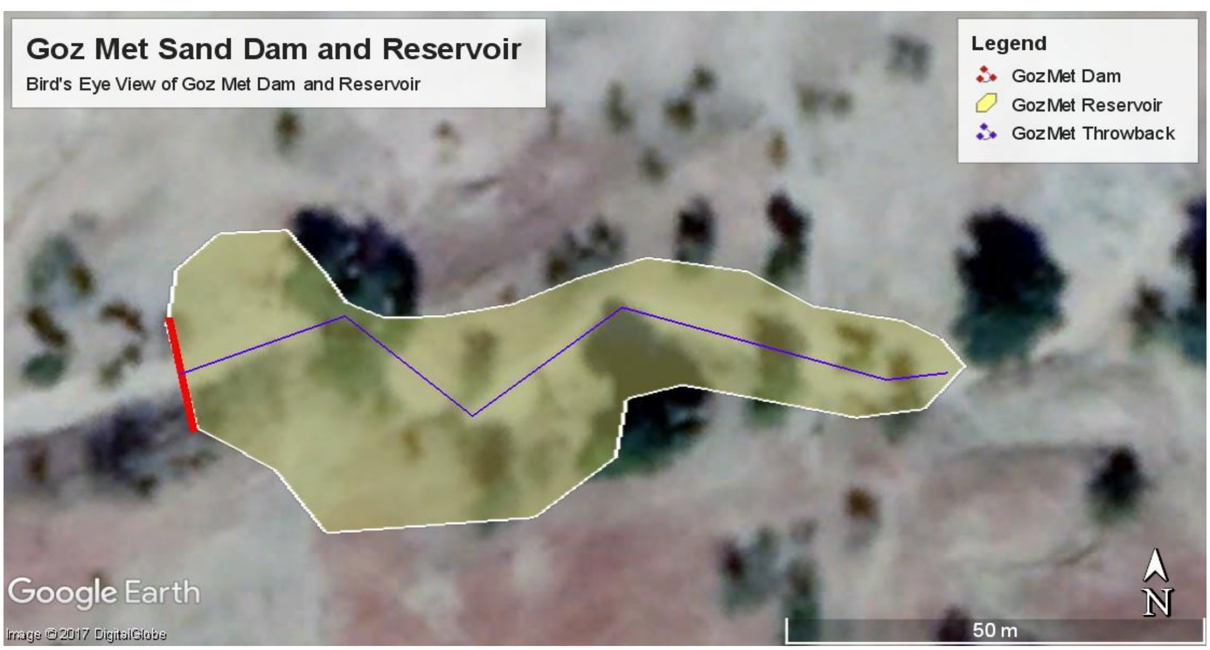



# Goz Met

13°33'6.57"N
21°47'32.46"E

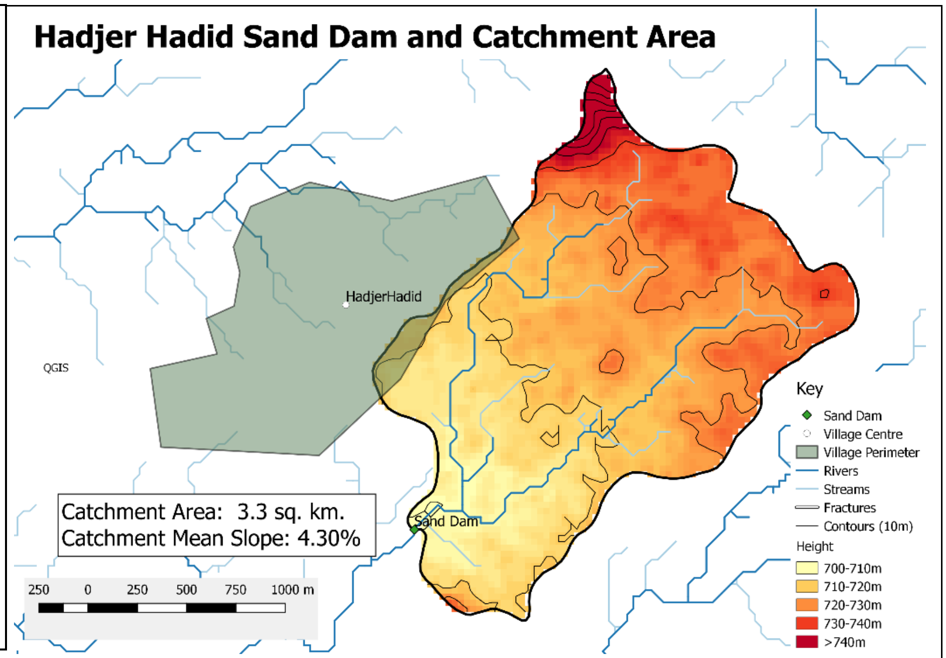


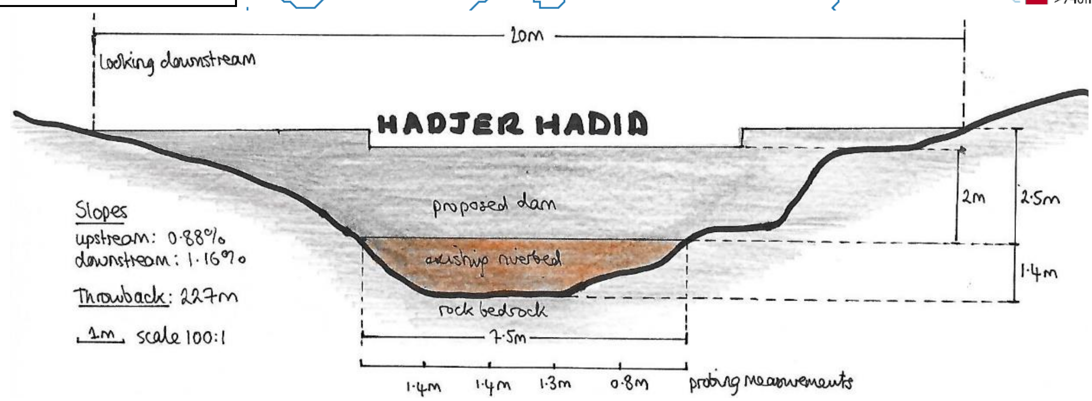



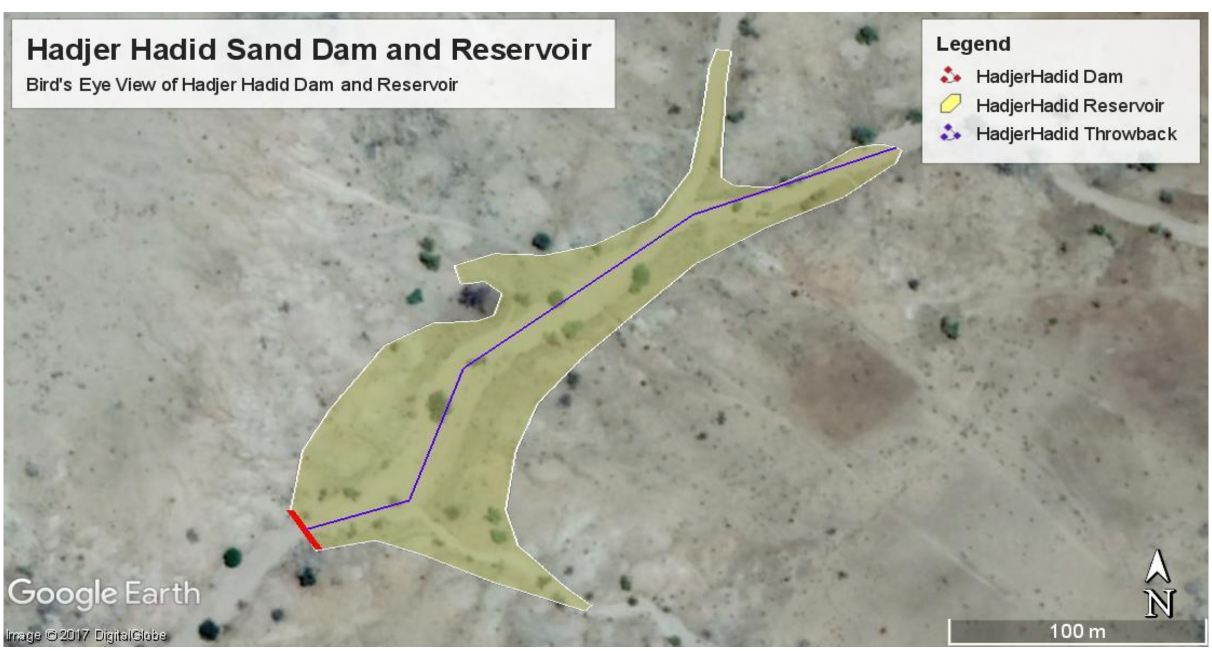



# Hadjer Hadid

13°25'58.44"N
21°40'6.48"E

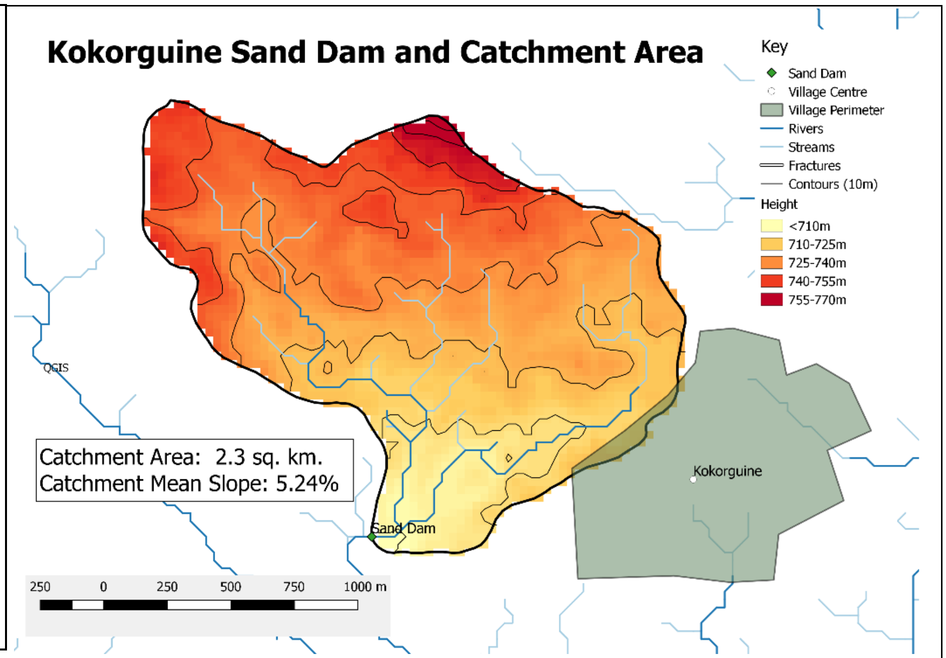


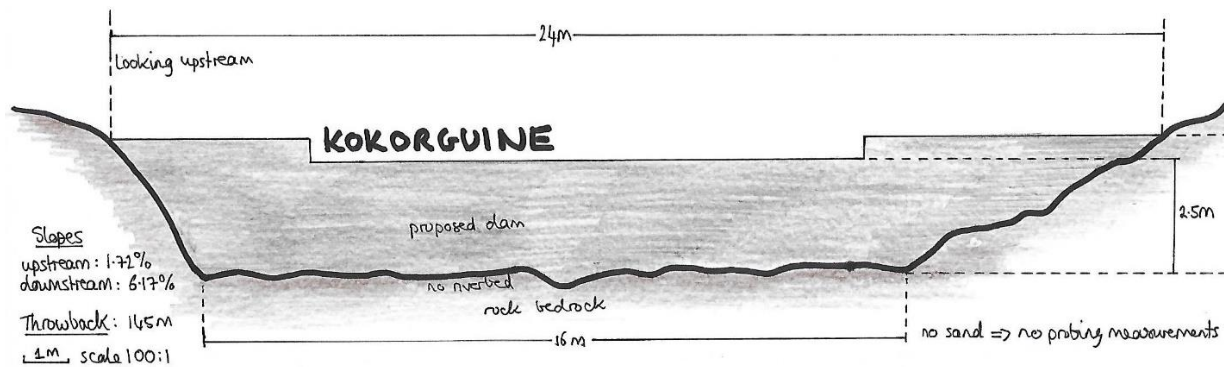



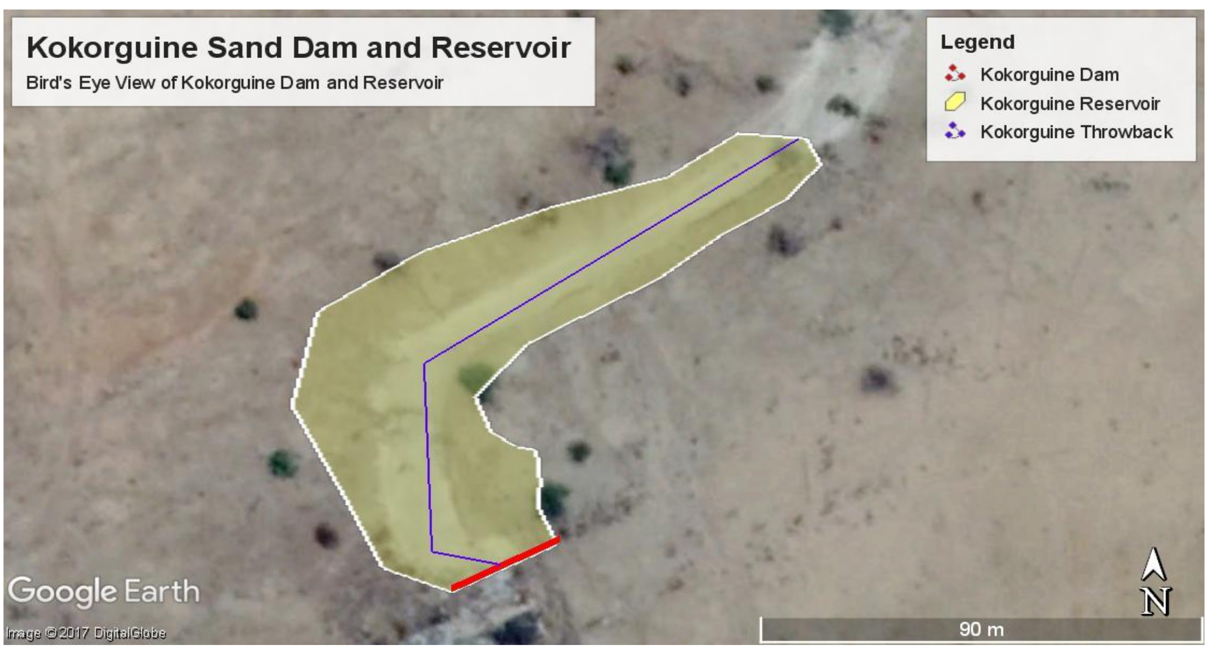



# Kokorguine

13°28'49.02"N
21°38'54.67"E

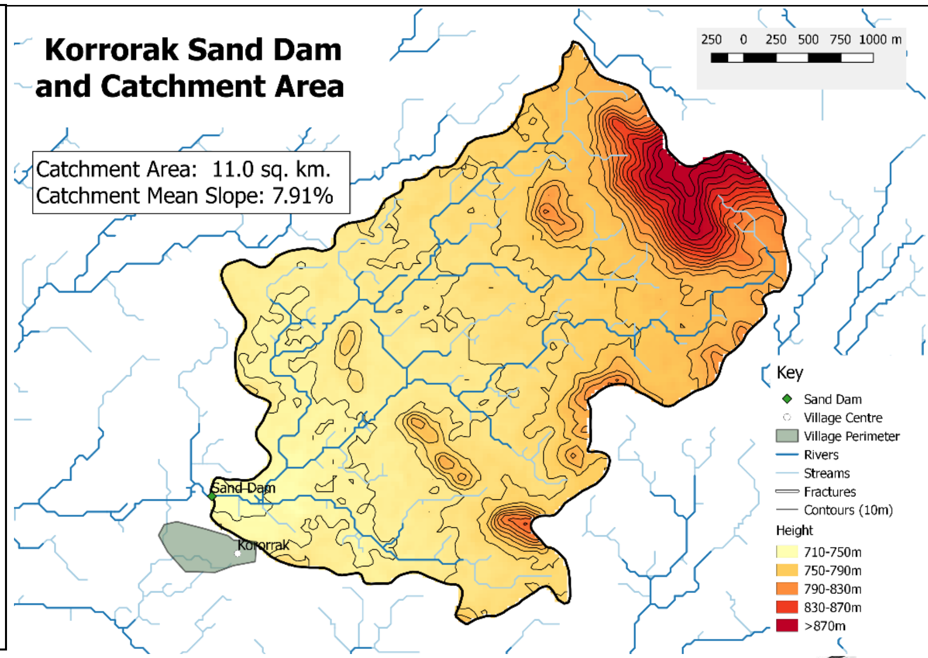


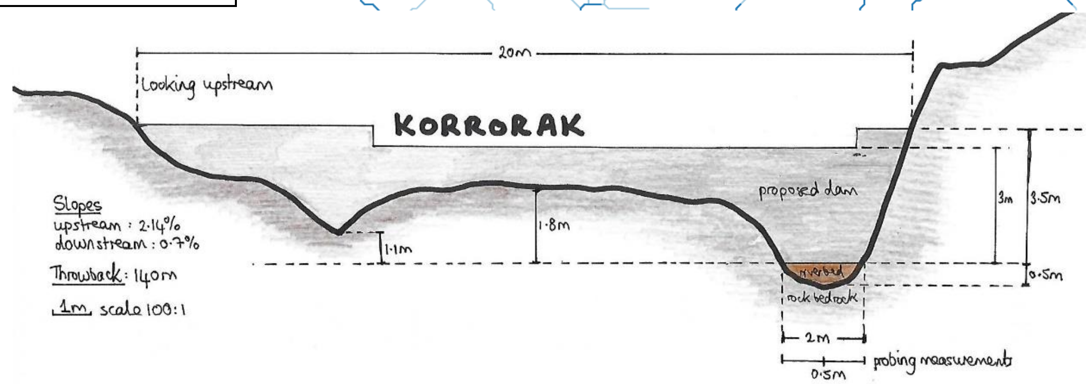



# Korrorak

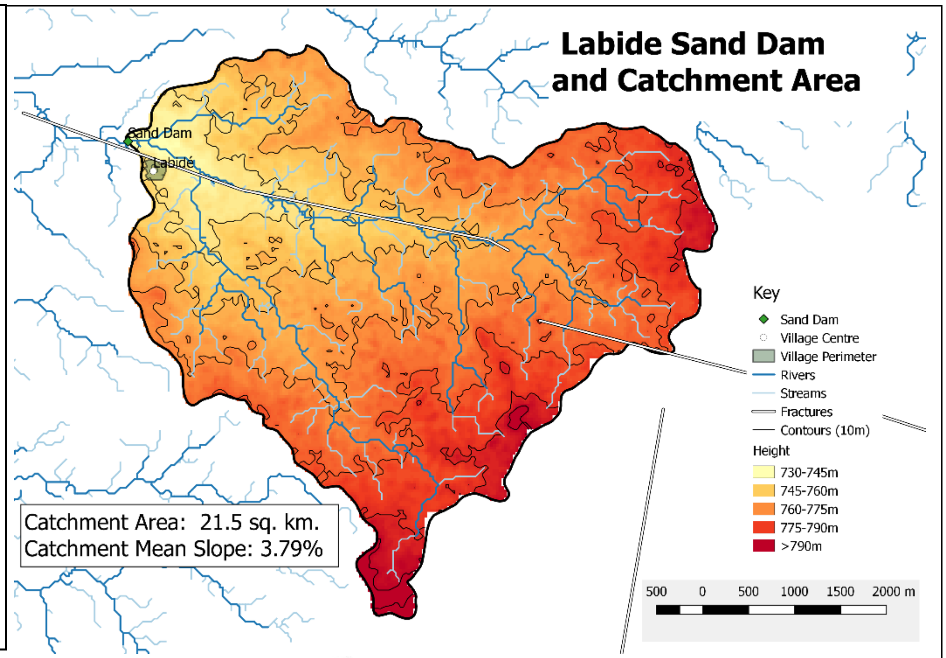
13°24'53.68"N
21°41'28.21"E

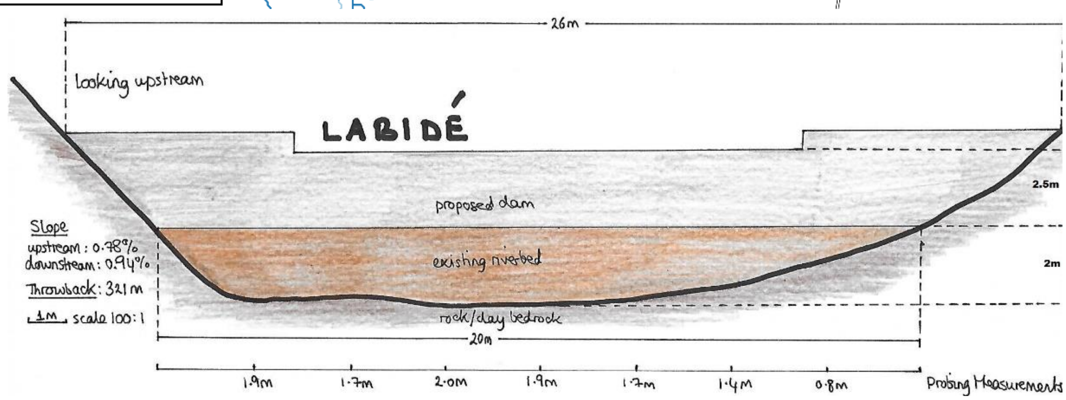



## Labide

13°22'14.52"N
21°43'26.40"E




# Louma Arab

13°32'15.18"N
21°49'0.60"E