www.RUVIVAL.de

TUHH
Hamburg University of Technology

aww
Institute of Wastewater Management and Water Protection

HOOU

RUVIVAL
Publication Series

06

12/2020

RUVIVAL Publication Series Volume 6

Founder & Editor in Chief
Ruth Schaldach

Co-Editors
Tina Carmesin
Carla Orozco Garcia

Layout & Design
Carla Orozco Garcia

Authors
Berenice Lopez Mendez
Lukas Schreiner
Samuel Duval

Address
Institute of Wastewater Management
and Water Protection
Eißendorfer Straße 42
21073 Hamburg

Identification
ISSN: 2567-8531
DOI: https://doi.org/10.15480/882.3075
URN: https://nbn-resolving.org/urn:nbn:de:gbv:830-882.0113034

December 2020

www.RUVIVAL.de

Stay in touch

Website: https://www.hoou.de/projects/ruvival-english/

E-mail: ruvival@tuhh.de

Picture credits can be found at the end of the paper.

Please cite as indicated in the paper.

Please consider the environment before printing.

From the Editor

Preface by Ruth Schaldach

This is the sixth volume of the RUVIVAL Publication Series. This open access publication series is developed within the e-learning project RUVIVAL, which you can visit under www.ruvival.de or www.hoou.de/projects/ruvival-english.

Our project is part of an initiative developed by the City of Hamburg together with all public universities in Hamburg to establish the Hamburg Open Online University (www.hoou.de). RUVIVAL is one of the first HOOU pilot projects and dedicated to sharing knowledge necessary to face rising environmental challenges, especially in rural areas. The RUVIVAL production phase has finalised and this will be the last issue in the series with one last literature review.

RUVIVAL collects practices and research conducted at the Hamburg University of Technology (TUHH), but also from all over the world. Each contribution in the publications is connected to further interactive multimedia material, which can be found, read, tested, watched, shared and extended on the RUVIVAL website, sorted by topic into several toolboxes (https://www.ruvival.de/toolbox/). However, all materials will be stored for long term use on the HOOU platform and you can find the extended material related to the following text on Sand Dams here:

www.hoou.de/projects/sand-dams

Each volume of the RUVIVAL Publication Series takes on a topic, which represents a cornerstone of sustainable rural development. The approach draws a systematic and interdisciplinary connection between water, soil, nutrition, climate and energy. Measures which enable sustainable use of land resources and improvements of living conditions are reviewed and new ideas developed with consideration of their different social, political and demographic contexts.

The following literature review was developed by a group of master students starting their research and text work in WS 2018/19 on sand dams. This is a water conservation technique, which is simple, low cost and low in maintenance if applied well and this text provides information to do so. During the review process we invited again the broader public and other students in the review process. After this extensive review and discussion process we are now happy to publish this literature review.

Sand Storage Dams: A Tool to Cope with Water Scarcity in Arid and Semi-arid Regions

Berenice Lopez Mendez, Lukas Schreiner and Samuel Duval

'Drylands are home to more than two billion people and are characterised by frequent, severe droughts. Such extreme events are expected to be exacerbated in the near future by climate change. A potentially simple and cost-effective mitigation measure against drought periods is sand dams. …sand dams enhance the resilience of marginal environments and increase the adaptive capacity of drylands. Sand dams can therefore be a promising adaptation response to the impacts of future climate change on drylands.'

(Ryan & Elsner 2016, p. 2087)

Please cite as: Lopez Mendez, B, Schreiner, L, & Duval, S 2020, 'Sand Storage Dams: A Tool to Cope with Water Scarcity in Arid and Semi-arid Regions', in R Schaldach (ed), RUVIVAL Publication Series, Volume 6, Hamburg, pp. 4 - 19, <https://doi.org/10.15480/882.3075>.

Abstract

A sand storage dam is a type of groundwater dam, a rainwater harvesting technique consisting of both an impermeable structure built across sandy riverbeds in seasonal streams and a crest raised above the riverbed. These have the potential to increase the water storage capacity and the yield potential of seasonal sandy rivers by trapping coarse sediments coming from the upstream catchment area in the dam. The optimal performance of a sand storage dam depends strongly on the proper selection of a suitable siting place, a tailor-made spillway design, which minimises the risk of siltation and appropriate construction procedures. While water in sand storage dams is of good quality, this can be affected during abstraction, transportation or storage.

Keywords: *sandy riverbeds, water harvesting, sand-abstraction, abstraction system, siltation, reclamation activities*

Introduction

Sand storage dams are impermeable structures built across sandy riverbeds in seasonal streams with a crest raised above the riverbed (Lasage et al. 2008). This barrier traps coarse sand sediments transported by runoff and stores water in the voids of the accumulated material (Hanson & Nilsson 1986). A multistage spillway design aims to maximise the water yield capacity of the sand storage dam, in order to fulfil the water needs of riparian communities during dry periods (de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018).

Sand storage dams are considered a type of groundwater dam, a macro-catchment water harvesting method that intercepts runoff, stores it in the sand and helps overcome water shortage during dry seasons (Biazin et al. 2012; Datta 2019; Hanson & Nilsson 1986). Sand storage dams are also considered an in-channel modification technique, a managed aquifer recharge method (Dillon 2005; Gale & Dillon 2005; Tuinhof et al. 2003).

As reviewed by Biazin et al. (2012), rainwater harvesting and management (RWHM) techniques comprise practices of rainwater collection, storage and reuse, as well as land-use measures. In arid and semi-arid regions, precipitation is highly variable in space and time and is frequently insufficient to allow crops to complete their growth cycle (Jaeger et al. 2017; Teel 2019). Therefore, RWHM practices are used to supply domestic or agricultural water needs, to reduce surface runoff and evaporation, and also enhance infiltration (Biazin et al. 2012). In this regard, Lasage & Verburg (2015) suggest that large communal water harvesting structures, such as groundwater dams, have a lower cost per unit of captured water than small household storage structures. However, the former may require a larger initial investment and specialised technical knowledge (Lasage & Verburg 2015).

The main aim of this literature review is to provide an overview of sand storage dams. First, background information related to sand abstraction systems and the functioning principles of groundwater dams are reviewed. Second, a general overview of different characteristics of sand storage dams is given. Then, necessary considerations are discussed, essential for designing and later for building a functioning, efficient and long-lasting sand storage dam. Additionally, safe water extraction and challenges in the implementation process are considered. Finally, the siltation phenomenon is shortly described, along with a summary on how silted-up sand dams can be further utilised (e. g. for riverbank reclamation activities or as an erosion prevention approach).

Seasonal Sandy Rivers and Groundwater Dams

Numerous researchers emphasise the importance of seasonal sandy rivers as a source of water in arid and semi-arid regions (Biazin et al. 2012; Datta 2019; Hussey 2007; Wipplinger 1958). When referring to the location of groundwater dams, the terms ‘seasonal’ and ‘ephemeral’ are used to describe the flow pattern and are sometimes used interchangeably, depending on the authors (Lasage et al. 2008; Lasage & Verburg 2015; Nissen-Petersen 2000; Nissen-Petersen 2006). De Trincheria et al. (2015) distinguish between the terms ephemeral and intermittent as two types of seasonal rivers. A similar situation can be identified between the terms ‘river’ and ‘stream’ (Lasage et al. 2008; Nissen-Petersen 2000; Nissen-Petersen 2006). In this case, a distinction is made in regard to the size of the water channel. Rivers are considered to be deeper and larger than streams (Datry, Bonada & Boulton 2017a). On top of that, eds Datry, Bonada & Boulton (2017b) give an extensive description about intermittent rivers and ephemeral streams.

Ephemeral streams are considered to flow directly in response to precipitation and to have flow patterns of short duration and low predictability (Datry, Bonada & Boulton 2017a; Goodrich et al. 2018; Hadley 1968). An intermittent river has a larger flow duration than an ephemeral stream. The flow fluctuates in response to temporal cycles, maintaining a continuous flow during wet periods (Datry, Bonada & Boulton 2017a; de Trincheria et al. 2015).

Ephemeral streams are widely spread in drylands[1] (Goodrich et al. 2018; Thornes 2009). These regions are characterised by brief, high intensity rainfall, a low average annual precipitation, and a strong spatial, seasonal and inter-annual variability (Pereira, Cordery & Iacovides 2009; Thornes 2009). Also, runoff is variable and the flow patterns in watercourses are of short duration and low predictability (Datry, Bonada & Boulton 2017a; Jaeger et al. 2017). Further, groundwater contributions are limited (Jaeger et al. 2017). In these regions, the precipitation to potential evapotranspiration ratio (aridity index, AI) is less than 0.65 (eds Cherlet et al. 2018, p. 72; Maliva & Missimer 2012, p. 24).

Sand rivers are defined by Walker et al. (2018) as unconsolidated alluvial deposits along watercourses. Where geology of low permeability is found underlying a sand river, an alluvial river aquifer is formed (Walker et al. 2018). Surface runoff from intense flows is the predominant form of recharge in alluvial aquifers, as the flood travels down a seasonal river after the river sand bed was saturated (Seely et al. 2003; Walker et al. 2018; Wekesa et al. 2020).

The amount of water that is infiltrated and stored in the interconnected voids of the unconsolidated sediments is typically described as the effective porosity of the alluvial material (Brassington 2017; Julien 2002). However, not all water can later be extracted; an indicator of the amount of water that can be drained from an aquifer is the specific yield (Brassington 2017). Unconsolidated sediments generally tend to be more permeable; this means that they have a high specific yield (Brassington 2017).

Seasonal sandy streams are a relatively effective and cheap source of water, which have the potential to fulfil the water needs of local communities (Lasage et al. 2015). A potential for water storage and abstraction exists in places where alluvial river aquifers have sufficient accumulation of coarse sand or gravel and where an underlying impervious or low-permeability layer is found to prevent seepage losses (Hanson & Nilsson 1986; Hussey 2007).

To increase the yield capacity of seasonal sandy rivers, the use of groundwater dams is recommended. There are two types of groundwater dams: subsurface dams and sand dams (Hanson & Nilsson 1986).

In a water stream, where a natural deposit of sand takes place, the construction of a subsurface dam helps to stop the underground water flow and to increase the natural water storage below ground (Hanson & Nilsson 1986; Hussey 2007). Hanson & Nilsson (1986) explain that when the foundations of a sand dam are constructed, a trench is excavated in the riverbed in order to reach the bedrock. Therefore, a subsurface dam can first be used to enhance the water yield in a sandy river. And later, the reservoir storage capacity can be increased by expanding the dam above ground (Hanson & Nilsson 1986). A simplified decision flowchart to both select between a sand storage dam and a subsurface dam and to also

[1] Drylands cover around 40 % of the world's land (eds Cherlet et al. 2018, p. 72).

determine if there is high siltation potential is given by de Trincheria et al. (2016).

Basic Hydrogeological Principles of Sand Dams

In a watershed, large quantities of eroded material are washed while rainwater drains into a particular stream; this material is also known as washload (Hicks & Gomez 2016). The washload constitutes a large part of the sediments transported by watercourses (Hussey 2007; Julien 2002) and is typically composed of clay, silt and fine sand (Hicks & Gomez 2016). Another source of sediments is the bed-material-load derived from the riverbed, typically composed of gravel and sand. The total transported material, called sediment load, consists of silt, sand, gravel and boulders, among others (Chanson 2004).

The most common forms of sediment transport in watercourses are bed- and suspended-load (Imran & Parker 2008). The bedload moves along the riverbed sliding, rolling or saltating and it is only found near the riverbed (Chanson 2004; Imran & Parker 2008). Particles in the suspended load are lifted and dispersed through the flow by turbulence (Armanini 2018; Hicks 2004). The unconsolidated sediments that are deposited and accumulated along the watercourses are called alluvium (Bridge 2004; Nanoso & Gibling 2004).

During rain events, sediments are transported along seasonal rivers by the runoff from an upstream catchment area. The watercourse gradient will determine the size of the sediments deposited along the riverbed (Hussey 2007). Rivers transport sediments from the upstream catchment area towards the dam built across the riverbed. The sediments slow down and settle in front of the dam. Thus, over time, the sand reservoir fills completely with sediments, forming an artificial alluvial aquifer, which stores water from the rainy season in the voids between the sand particles (Lasage et al. 2008; Lasage et al. 2015). Figure 1 illustrates the concepts of bed- and suspended-load described by Imran & Parker (2008) and Hicks & Gomez (2016) and also the concept of accumulation of sediments behind the wall of the sand storage dam illustrated by Onder & Yilmaz (2005).

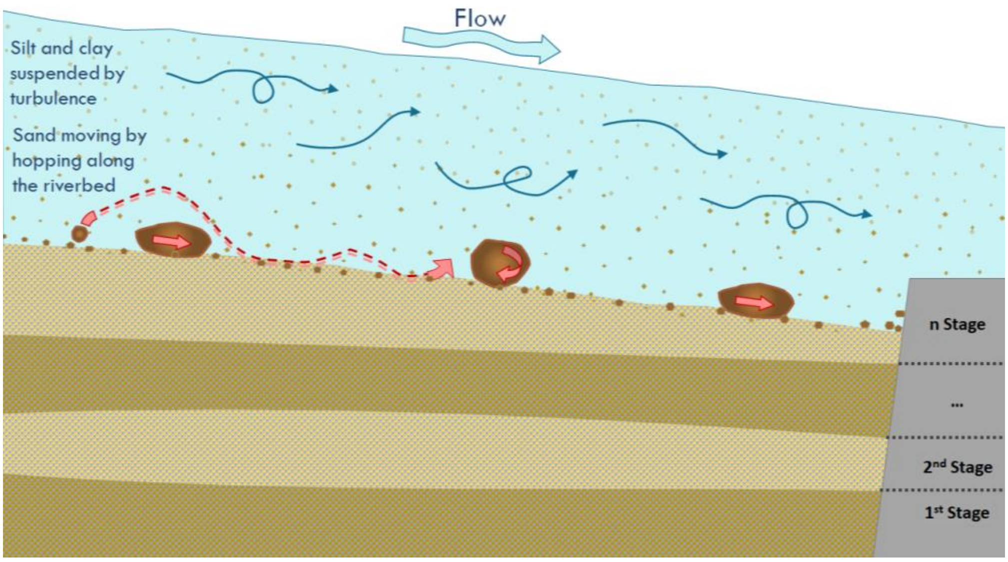

Figure 1 Bedload Transport & Concept of a Sand Dam

During the rainy season or any rain event, the sand storage dam is recharged. If it exceeds the storage capacity, excess water simply flows over the dam spillway (Onder & Yilmaz 2005). Then, water can be extracted from the reservoirs by the use of structures such as a waterhole, a hand-dug well, an infiltration pipe, a well shaft in the riverbank, an intake chamber with elevated water tank (Nissen-Petersen 2006) or by using a pump.

Identification and Selection of a Suitable Construction Site

Several authors point out the importance of site selection, as it greatly impacts the performance of a sand storage dam (de Trincheria et al. 2015; de Trincheria et al. 2016; Hanson & Nilsson 1986; Hussey 2007; Nissen-Petersen 2000; Nissen-Petersen 2006; RAIN 2008). Therefore, accuracy in site assessment is necessary in order to optimise dam design and to provide long-lasting benefits to the community (RAIN 2008). Further, de Trincheria et al. (2015) identify and discuss key factors affecting the performance of sand storage dams related to incorrect siting procedures.

The purpose of conducting basic studies is to identify those riverbeds that are suitable for sand-abstraction and to select optimum abstraction sites (Hussey 2007). Also, Hussey (2007) and RAIN (2008) point out the importance of selecting a site that is not only technically appropriate, but also socially suitable. There are three steps in the selection of a site: identification of a potential catchment, field inspection of the potential riverbed, and probing and evaluation of the properties of different section of riverbed (RAIN 2008). Moreover, Brassington (2017) describes an even more detailed breakdown of activities related to a hydrogeological survey and lists the following phases: desk study, walkover survey, exploration, monitoring programme, data management, water balance and conceptual model.

Nissen-Petersen (2000; 2006) discusses specific characteristics that a potential site has to comply with in order to produce enough coarse sediments and build a functioning sand storage dam. Some of the primary factors of an optimal site are as follows:

- The site is a valley floor in a seasonal sandy riverbed where coarse sediments transported by runoff are accumulated. The upstream catchment area should be large enough to provide a sufficient volume of coarse sand (Hussey 2007; Nissen-Petersen 2000; Nissen-Petersen 2006).
- The area should not contain calcrete, halite or other salty rocks, as these can dissolve in water and turn it saline (Nissen-Petersen 2006, p. 5; RAIN 2008, p. 11).
- The slope at the construction site should be flat to gentle, around 1 - 5 % (Hanson & Nilsson 1986, p. 499; RAIN 2008, p. 8). At this slope, two contrary effects are at equilibrium. A steep slope leads to a high flow velocity; therefore, only the coarsest sediments (gravel, boulders) will settle and the infiltration rate will be low. On the other hand, an area with an extreme flat slope leads to a low flow velocity and consequently, fine sediments settle producing siltation and reducing the water yield. As coarse particles and high infiltration are desired, an optimal siting site needs to be selected in order to maximise water storage and yield potential (Gur & Spuhler 2018; Hanson & Nilsson 1986; Hussey 2007; Klopfer 2010; RAIN 2008).
- The riverbanks must be high, and the width must be less than 25 m. The wing walls can be fixed to the sides and no ex-

pensive reinforcement of the wall is needed (Nissen-Petersen 2006, p. 49; RAIN 2008, p. 8, 12).

- It is recommended to site the sand storage dam in a straight section of the river, where there are no bends 50 m upstream and 25 m downstream, in order to prevent the damage to wing walls and the erosion of the riverbanks (Nissen-Petersen 2000).
- There is an impermeable ground layer of clay or non-fractured rock beneath the dam and a natural subsurface dyke that prevents seepage (Hussey 2007; Nissen-Petersen 2000; Nissen-Petersen 2006; RAIN 2008).
- Sand dams should be sited on top of an already existing alluvial aquifer in order to optimise its performance and cost-efficiency. The advantage is that natural reservoirs usually already contain sands of a high permeability and yield, which can interact with the artificial sand reservoir by infiltration and capillary forces (de Trincheria et al. 2015).

After a potential site has been identified and an agreement with the community has been made, Nissen-Petersen (2000; 2006) and RAIN (2008) recommend conducting a detailed survey.

The site assessment is an important and complex undertaking. Hydrological information is often expensive, inaccurate and/or not sufficient for proper assessment, particularly in arid and semi-arid areas (de Trincheria et al. 2016). Hussey (2007) gives a detailed overview of practical observations and tests for the initial identification of potential sites within suitable rivers. These include the following: the extent of the river catchment area, the size of the river and volume of sediment, the gradient of the river, and characteristics of the sediment. Further, Nissen-Petersen (2000; 2006) compiles traditional knowledge and simple and low-cost experienced based probing techniques for a practical and affordable site assessment. Some of the methods mentioned by Nissen-Petersen (2000; 2006) and Hussey (2007) for a site characterisation include the investigation of:

- local community knowledge,
- estimation of water level depth by vegetation indicators,
- height and shape of riverbanks,
- porosity of sand,
- gradient of the hillside,
- expected storage capacity and yield of the dam reservoir.

After a potential riverbed section has been selected, Hussey (2007) recommends to determine the potential water storage capacity and yield by means of an accurate grading of the sediments. For this reason, extensive knowledge about the potential site and its physical characteristics is required. Further, a comprehensive understanding of geophysical and hydrogeological concepts related to runoff and sediment is also necessary. The characterisation of the selected riverbed section is required in order to estimate the potential storage and yield capacity (Hussey 2007; Klopfer 2010; Quilis et al. 2009; Walker et al. 2018).

However, to predict the amount of coarse sediments which will be transported in the runoff is extremely complicated (de Trincheria et al. 2015; de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018). Runoff transports eroded materials, which are deposited when the energy of the flow cannot continue to carry them. The coarse sediments (e.g. those found in the bedload) account for only between 5 - 8 % of the total transported sediments (Alexandrov et al. 2009, p. 11; de Trincheria et al. 2016, p. 3; Powell et al. 1996, p. 394). In addition, the bedload transport is highly variable, depending on individual rain events. The rainfall intensity has to reach a minimum threshold in order for bedload transport to even take place. After studies performed on a gravel-bed ephemeral stream, Powell et al. (1996, cited in de Trincheria et al. 2016) and Alexandrov, Laronne & Reid (2003, cited in de Trincheria et al. 2016) showed that in one out of three runoff events, only fine sediments are entrained.

General Design Recommendations

Once an optimal location has been defined, the sand storage dam has to be designed according to the given conditions of the site. Nevertheless, surveys are always required in order to find a fitting construction site and to determine the design parameters and the type of groundwater dam (Hanson & Nilsson 1986; Nissen-Petersen 2000; 2006). The construction materials can vary according to the affordability and availability of local resources and labour at the construction site (Nissen-Petersen 2000; Nissen-Petersen 2006).

The construction of the dam, especially the stage height, has to be adjusted so that only the coarse fraction of the sediments is retained and most of the fine material is carried over the spillway. According to de Trincheria et al. (2016), the determination of the stage height is thereby a case-by-case decision. Although the stage construction method of sand storage dams was already described by Wipplinger in 1958, many sand dams have been built in one step (de Trincheria et al. 2015; de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018). There are no unified criteria on the technical design. This issue requires further data collection and research (de Trincheria et al. 2015; de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018).

According to de Trincheria et al. (2016), long-term studies are often too expensive in arid and semi-arid areas; therefore, they introduce a precautionary decision guide which contains stage height recommendations based on relevant long-term scientific and empirical studies, summing up the most relevant literature. This decision guide describes the stage height as a function of the key hydrogeological variables with the strongest influence on bedload transport, which take into account:

- the predominant particle grain-size of the original riverbed (coarse, medium, fine),
- the type of seasonal riverbed (intermittent or ephemeral) and,
- the number of rainy seasons per year.

The guide then suggests a stage height for good or poor years, depending on the desired predominant particle size of the final reservoir (de Trincheria et al. 2016). In general, a minimum stage height of 20 cm is suggested if the maximum height can be reached within the project time frame (de Trincheria et al. 2016, p. 9). For example, for an ephemeral stream, a typical final spillway height of 1.5 – 5 m can be reached within a typical project time of 1 – 3 years under an unimodal rainfall season during good or normal rainfall years (de Trincheria et al. 2016, p. 5-6, 8).

A practical guide on survey, community engagement, design and construction steps of sand storage dams is given by Maddrell (2018). Also, an overview on the planning steps is given by RAIN (2008) in 'A practical guide to sand dam implementation'. Furthermore, Nissen-Petersen provides a manual (2000) and a technical handbook (2006), where simple techniques and affordable construction systems for extracting water from sandy rivers are described.

Overview of Construction Procedures

Once a site survey is conducted and a step-height is defined, the construction can be planned. The most cost-efficient method is to build the base (underground section) and the wing walls according to the final height. The spillway in the centre can be raised step-by-step (de Trincheria et al. 2016). The construction process usually follows the steps below.

1. A deep trench is dug across the riverbed where there is a natural underground dyke in order to increase the storage volume (de Trincheria & Nissen-Petersen 2015). In order to avoid seepage, the trench is dug until either the bedrock layer is reached or there is at least 1 m of another stable, impermeable soil layer (Nissen-Petersen 2006, p. 48). If built on top of an aquifer, it also needs to be sealed by reaching down to the rock layer (Klopfer 2010). Then, the first stage above ground can be built.
2. The wall is raised step by step. The next step can be built once the previous stage is filled with runoff (Gur & Spuhler 2018).

The materials used to construct the dam depend on local availability. Sand dams are defined by the materials used to construct them (Nissen-Petersen 2000). These types are the following:

- stone-masonry dams made of concrete blocks or stones,
- steel reinforced concrete dams,
- earth dams with impermeable clayey soil or black soil,
- dams made of other local materials, e.g. from a termite hill, which is also used for sealing houses (Klopfer 2010).

Concrete dams are more stable, but the most reasonable option always depends on what is available and the expertise of local craft labour. For concrete dams, waterproof Portland cement is necessary, which may be difficult to obtain. Also, the large water demand for all these types of dams might be challenging and needs to be considered. Nissen-Petersen (2006) gives some rules of thumb for the dimensions of the dam wall and wing walls (Figure 2):

- the width of dam base is ¾ of the dam height,
- the wall thickness is 55 % of the dam height,
- the crest thickness is 1/5 of the dam height,
- the wall leaning downstream has a gradient that is 1/8 of the dam height,
- the apron must be reinforced; placing large stones onto which the spill-over will fall will reduce the spill-over force, preventing apron concrete undercutting,
- the wing walls on the sides should be built with an angle to the main dam in order to prevent overflowing, especially if the riverbank is low.

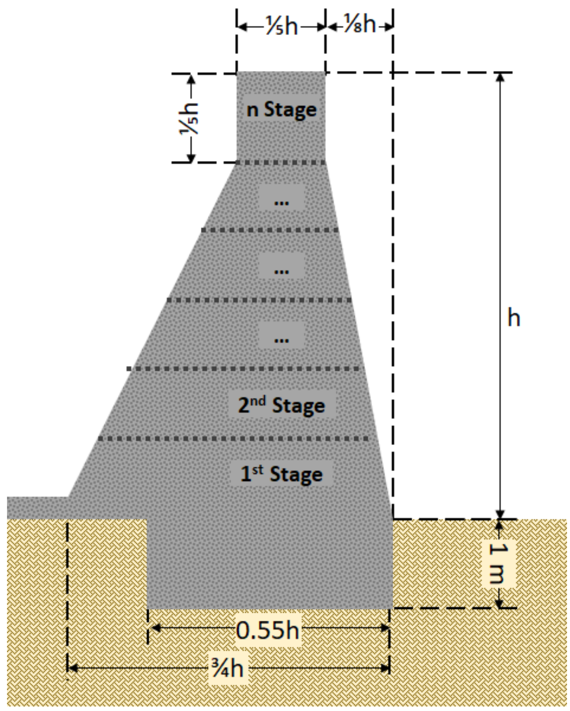

Figure 2 Dam Wall Dimensions, Based on Nissen-Petersen 2006 (2006, pp. 51–2)

Further details on the construction criteria and of sand storage dams can be found in the handbook 'Water from Dry Riverbed' by Nissen-

Petersen (2006) and in the 'Sand Dams Manual' by Maddrell (2018).

Water Separation and Abstraction from Sand Dams

There are different methods to separate and extract water stored in a sand dam. Hussey (2007) gives a comprehensive description of sand-abstraction systems for the effective separation of water from sediments. The selection of the most suitable system will depend on the sediment conditions, the materials available and the local community requirements (Hussey 2007).

The simple, but less favoured method is the scoop hole. A hole is dug by hand in the sand, and water is drawn as it seeps into the hole. A scoop hole can easily be damaged by the river flow and filled by runoff sediments (Hussey 2007; Nissen-Petersen 2006). When scoop holes are not effectively managed, these could compromise the water safety of the whole reservoir by introducing pollutants (Quinn et al. 2018). Water is filtered through the riverbed over a long distance. Therefore, holes used by the local population should be close to the dam. Also, animals should be kept away to prevent manure contamination. Additionally, water abstracted with a scoop hole should always be boiled before drinking (Hussey 2007; Quinn et al. 2018; RAIN 2008).

Another abstraction method is to construct a well. This is a better alternative since water is always kept underground and protected from evaporation and contamination (Hussey 2007). For better sustainability, the well needs to be covered and properly maintained. The water lifting can be done with a rope and a bucket or with a hand, centrifugal or submersible pump. Hand pumps are often the easiest to maintain for small communities. The location of the well is very important. Both technical and social aspects need to be considered. The location where the water yield is the highest is often where the riverbed is the deepest. This will require an adequate protection to prevent damages to the well caused by floods. An alternative is to position the well in the riverbank. Even though this will increase the initial cost, the potential damage from floods is reduced and the maintenance will be less demanding. Furthermore, wells are recommended to be built close to the previous location of scoop holes used by the community. This prevents the local population from continuing to drink water which may be contaminated (Hussey 2007; Nissen-Petersen 2006; RAIN 2008).

A third water extraction method consists of an outlet tap connected to an infiltration pipe. This is a net of perforated pipes placed at the bottom of the riverbed through which water is collected and directed towards the tap. The pipe should be shielded so as to prevent sand and silt from entering. It should be located just above the impermeable layer and covered with a layer of coarse gravel and a layer of coarse sand. The tap can be located in the dam wall or on a borehole in the riverbank. However, it has some disadvantages. The outlet could weaken the structure of the dam wall and the maintenance of the system could be complicated and expensive (Hussey 2007; Nissen-Petersen 2006; RAIN 2008).

There are numerous output/lifting mechanisms such as by hand or bucket, tap, animal trough, hand pumps or diesel/electric/solar pumps (Hussey 2007; Maddrell 2018; Nissen-Petersen 2006). Maddrell (2018) and Hussey (2007) give an extensive overview of the intake and output mechanisms for water abstraction, while Nissen-Petersen (2006) describes some of the most cost-efficient and low maintenance water abstraction systems for riverbeds.

A study carried out by Quinn et al. (2018) suggests that the quality of water in sand storage dams represents a low microbiological risk. In a sand storage dam, runoff permeates through the sand storage dam, similar to a slow-sand-filter (Quinn et al. 2018). Also, the water stored in the sand storage dam is protected from contamination and sunlight (Hussey 2007). These factors result, in general, in a good water quality (Avis 2016).

However, water quality could be affected during abstraction, mostly if the abstraction method is a scoop hole, which shows higher levels of microbial contamination than covered wells (Quinn et al. 2018). Also, Avis (2016) states that contamination of water may be introduced during transport and storage before final use. Therefore, hygienic training and maintenance are extremely important to preserve water quality from sand storage dams (Avis 2016).

Benefits and Constraints of Sand Dams

In a sand storage dam, the water is stored in the sand, shielded from the sun and wind (Klopfer 2010). Evaporation is limited to the upper soil layer as it occurs only until a soil depth of 60 cm (Liu et al. 2015, p. 8699; Nissen-Petersen 2000, p. 2). If the water is stored underground, it is also shielded from contamination. Similarly to what happens with groundwater, the infiltration of pollutants is delayed or even totally prevented, as the sand reservoir acts as a natural filter (Avis 2016; Klopfer 2010; Onder & Yilmaz 2005; Quinn et al. 2018). Since there are no open water surfaces, the reproduction of malaria mosquitos is inhibited (Klopfer 2010; Yohannes et al. 2005).

Women oftentimes have to spend several hours a day and walk many kilometres in order to get water, which imposes a heavy physical burden on them (Hussey 2007; Nissen-Petersen 2006). A nearby sand dam can significantly reduce the distance and time to get water (Lasage et al. 2015). Residents have shown to use this saved time for more productive activities, like taking care of the household or generating income. Furthermore, with more water and time at hand, people are able to adapt and implement improved agricultural techniques. After comparing interviews in two communities, one with a sand storage dam and one without one, Lasage et al. (2008) concluded that the increase of water availability results in higher farm yields and an increase on the average income of farmers. Thus, a sand dam can lead to improved agricultural production and food security, as well as increased income (Hussey 2007; Lasage et al. 2008; Pauw et al. 2008).

There are a few negative influences on the downstream area. Between 2 – 4 % of the runoff water is retained (Aerts et al. 2007; Borst 2006, p. 6, 83; Klopfer 2010; Pauw et al. 2008, p. v, 48). However there are discrepancies between modelling approaches and results, that suggest that the downstream impacts are still uncertain (Lasage et al. 2015).

Each sand storage dam is a unique structure, whose design must be adapted to the specific conditions of the site to attain the maximum possible accumulation of coarse sediments. The storage and yield capacity can be maximised by choosing the right stage height (de Trincheria et al. 2015; de Trincheria, Leal & Otterpohl 2018; Nissen-Petersen 2000).

Special considerations must be made before selecting a sand storage dam as part of a water supply project. Sand storage dams have limitations. One of these is their rather high technical complexity, at least in comparison to subsurface dams (Butterworth, Adank & Boelee 2014; Klopfer 2010). A sand storage dam has specific technical requirements that need to be fulfilled. For a functioning and efficient water supply, two things are essential: a fitting construction site (Ali et al. 2014; Hussey 2007; Nissen-Petersen 2006) and an optimal design (de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018).

Sand storage dams are a more expensive way of extracting water from sandy riverbeds in comparison to subsurface dams or other small scale structures (Lasage & Verburg 2015). In situations where the alluvial riverbed has a limited accumulation of sediments and the underground water reservoir is not large enough to hold sufficient water for all the residents, a sand storage dam can be a good alternative. The sand storage dam will increase the storage capacity and yield (Hussey 2007; Nissen-Petersen 2006).

Silted-up Sand Dams

Certain generally accepted design recommendations – including the evaluation of the catchment area, construction stages of the spillway, the height of the wing walls and the spillway – are well established and were discussed in previous sections. When those recommendations are not met, there is a high risk that the yield potential of the sand storage dam be significantly reduced (de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018). Inappropriately designed sand storage dams could lead to an accelerated siltation of the system.

Siltation is a phenomenon that affects the performance of sand storage dams, which means that the capacity of the dam to store and yield water is reduced (de Trincheria, Leal & Otterpohl 2018). As explained by Nissen-Petersen (2006), coarse sand must be trapped, while fine sand and lighter silt have to flow over the sand dam spillway. However, when a combination of soil, silt and clay is trapped behind the dam, this can result in a compacted hard layer that could significantly reduce the water yield (Nissen-Petersen 2006). An adequate design of the spillway in sand storage dams will significantly reduce the risk of siltation (de Trincheria, Leal & Otterpohl 2018).

In regard to the selected construction site, Nissen-Petersen (2006) recommends low gradient catchments and catchments that contain farmland should be avoided, as they originate silt and fine sand and slow down the velocity of flash floods. This allows fine particles to settle in the riverbed, generating siltation.

De Trincheria, Leal & Otterpohl (2018), de Trincheria et al. (2015) and de Trincheria et al. (2016) studied the performance of sand storage in arid and semi-arid areas and discuss factors that may lead to siltation and poor performance and how to minimise siltation. De Trincheria, Leal & Otterpohl (2018) point out that one of the main factors leading to siltation is the high inter- and intra-annual variability of bedload transport coupled with the construction of a one-stage spillway.

At best, a multi-year study of the sediment transport capacity and hydrodynamic flow variations in the stream should be conducted to estimate the stages and height of a spillway that will maximise the accumulation of coarse sediment at a specific site (de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018). However, this could be a complex and time-consuming task that could lead to high costs. An alternative could be a spillway raised in fixed stages of reduced height defined on a case by case basis (de Trincheria et al. 2016; de Trincheria, Leal & Otterpohl 2018).

The existence of several silted-up sand dams points out the need to offer suitable alternatives to these structures. Some alternatives proposed by de Trincheria et al. (2016) are:

- reconstruction of the spillway,
- dredging,
- holistic agricultural and land reclamation activities,

- application of a smart agroforestry system, as well as water and soil conservation practices to enhance the water retention capacity and,
- holistic riverbed and riverbank reclamation activities.

Sand storage dams are not isolated storage structures. They have the potential, in the long term, to increase the moisture within the soil profile and recharge groundwater (Quinn, Rushton & Parker 2019; Ryan & Elsner 2016). This provides soil and water conservation benefits along the adjacent riverbanks, increasing vegetation and reducing soil erosion (Knoop, Sambalino & van Steenbergen 2012). Raising the groundwater table has an effect on soil moisture, which in turn has a positive impact on vegetation in the surrounding areas of sand storage dams (Ryan & Elsner 2016).

Conclusion

Unconsolidated alluvial deposits with low permeability are found along sandy rivers; there, water is infiltrated and stored in the interconnected voids of the sediments. Hence, ephemeral sandy rivers are a suitable source of water, where unconsolidated alluvial deposits and an underlying low permeability layer exist.

Groundwater dams are a suitable rainwater harvesting technique to increase the water yield in ephemeral sandy rivers. A sand storage dam, which is a type of groundwater dam, is an impermeable structure built across sandy riverbeds in seasonal streams, with a crest raised above the riverbed. This structure traps coarse sediments coming from the upstream catchment area in the dam built across the riverbed. During the rainy season, runoff permeates through the sand stored in the dam. There, water is protected from the sun and wind, reducing evaporation losses. It is stored for further use during the dry season.

It is advisable to have a site assessment done with a multi-year study of the sediment transport capacity and hydrodynamic flow variations in the sandy river. However, due to economic and time constraints, there are also practical and affordable site assessment techniques that can be employed. The design of the sand storage dam, particularly the stage height of the spillway, should be adapted according to the conditions of the selected site. It is suggested that some factors, such as the predominant particle grain-size of the riverbed, the expected sediments in the reservoir, the type of seasonal river and the number of rainy seasons per year, should be taken into account.

The materials chosen for the construction will depend on local availability. Also, the water abstraction system will depend on the materials available and the local community practices. However, the high-quality water stored in the sand could be affected during abstraction, transportation and/or storage before use. Therefore, the abstraction method requires careful selection, and additional hygienic and maintenance training must be taught to the community.

Siltation is the result of the accumulation of clay and silt along with sand and leads to a significant reduction of yield potential. Though this is a natural phenomenon, siltation can be systematically minimised. Else, high costs, low yields and siltation could be faced. In contrast, well-designed sand dams are an effective tool for water harvesting and enhancing the water yield of pre-existing systems such as subsurface dams.

Image Credits

Figure 1 (p. 7) Bedload Transport & Concept of a Sand Dam <https://doi.org/10.15480/882.3075> by Berenice Lopez Mendez is licensed under CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0/>.

Figure 2 (p. 11) Dam Wall Dimensions
Based on Nissen-Petersen (2006, pp. 51-2).

References

Aerts, J, Lasage, R, Beets, W, Moel, H de, Mutiso, G, Mutiso, S & Vries, A de 2007, 'Robustness of Sand Storage Dams under Climate Change', *Vadose Zone Journal*, vol. 6, no. 3, p. 572.

Alexandrov, Y, Cohen, H, Laronne, JB & Reid, I 2009, 'Suspended sediment load, bed load, and dissolved load yields from a semiarid drainage basin: A 15-year study', *Water Resources Research*, vol. 45, no. 8.

Alexandrov, Y, Laronne, JB & Reid, I 2003, 'Suspended sediment transport in flash floods of the semiarid northern Negev, Israel', in E Servat (ed.), *Hydrology of Mediterranean and Semiarid Regions: Papers selected for the International conference held in Montpellier, France, from 1 to 4 April 2003*, IAHS publication, no. 278, IAHS Press, Wallingford, pp. 346–52.

Ali, SS, Al-Umary, FA, Salar, SG, Al-Ansari, N & Knutsson, S 2014, 'Evaluation of Selected Site Location for Subsurface Dam Construction within Isayi Watershed Using GIS and RS Garmiyan Area, Kurdistan Region', *Journal of Water Resource and Protection*, vol. 06, no. 11, pp. 972–87.

Armanini, A 2018, *Principles of River Hydraulics*, Springer International Publishing, Cham, viewed 9 December 2016, <https://en.wikipedia.org/w/index.php?oldid=749941221>.

Avis, O 2016, 'A Microbial Analysis of Water in Sand Dams and Associated Abstraction Methods', in S Furey (ed.), *Water for Everyone, – Vol.1 Papers & Films*, 7th RWSN Forum Water for Everyone, Abidjan, Côte d'Ivoire, 29 November - 2 December, 2016, Rural Water Supply Network, Skat Foundation, St. Gallen, Switzerland, pp. 730–46, viewed 4 August 2017, <https://rwsnforum7.files.wordpress.com/2015/11/proceedings-of-the-7th-rwsn-forum-2016-vol1.pdf>.

Biazin, B, Sterk, G, Temesgen, M, Abdulkedir, A & Stroosnijder, L 2012, 'Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa: A review', *Physics and Chemistry of the Earth, Parts A/B/C*, 47-48, pp. 139–51.

Borst, L 2006, 'Hydrology of Sand Storage Dams: A case study in the Kiindu catchment, Kitui District, Kenya', Master Thesis, Vrije Universiteit, Amsterdam, viewed 20 December 2018, <https://www.samsamwater.com/library/L_Borst_SA_de_Haas_-_Hydrology_of_Sand_Storage_Dams_-_A_case_study_in_the_Kiindu_catchment_Kitui_District_Kenya_-_rev1.pdf>.

Brassington, R 2017, *Field Hydrogeology*, 4th edn, John Wiley & Sons Ltd.

Bridge, JS 2004, 'Alluvium', in A Goudie (ed.), *Encyclopedia of geomorphology*, Routledge, London, pp. 19–21.

Butterworth, J, Adank, M & Boelee, E 2014, *Water supply from sand rivers for multiple uses: Case studies of multiple use of water in Ethiopia (MUStRAIN case 1)*, IRC International Water and Sanitation Centre, The Hague, The Netherlands.

Chanson, H 2004, *The hydraulics of open channel flow: An introduction; basic principles, sediment motion, hydraulic modelling, design of hydraulic structures*, 2nd edn, Elsevier Butterworth Heinemann, Amsterdam.

Cherlet, M, Hutchinson, C, Reynolds, J, Hill, J, Sommer, S & Maltitz, G von (eds) 2018, *World atlas of desertification: Rethinking land degradation and sustainable land management*, Publications Office of the European Union, Luxembourg.

Datry, T, Bonada, N & Boulton, AJ 2017a, 'General Introduction', in T Datry, N Bonada & AJ Boulton (eds), *Intermittent rivers and ephemeral streams: Ecology and management*, Academic Press, Elsevier, London, United Kingdom, pp. 1–20.

——(eds) 2017b, *Intermittent rivers and ephemeral streams: Ecology and management*, Academic Press, Elsevier, London, United Kingdom.

Datta, PS 2019, *Water harvesting for groundwater management: Issues, perspectives, scope, and challenges*, John Wiley & Sons, Hoboken NJ.

de Trincheria, J, Leal, WF & Otterpohl, R 2018, 'Towards a universal optimization of the performance of sand storage dams in arid and semi-arid areas by systematically minimizing vulnerability to siltation: A case study in Makueni, Kenya', *International Journal of Sediment Research*, vol. 33, no. 3, pp. 221–33.

de Trincheria, J & Nissen-Petersen, E 2015, 'Sand Storage Dams: Performance, cost-efficiency, working principles and constraints', in E Boelee & J de Trincheria (eds), *Unlocking the Potential of Rainwater*, Presentations of the Practical Workshop, International Symposium on Rainwater Harvesting and Resilience, Addis Ababa, 1 - 12 June 2015, RAIN.

de Trincheria, J, Nissen-Petersen, E, Leal Filho, W & Otterphohl, R 2015, 'Factors Affecting the Performance and Cost-Efficiency of Sand Storage Dams in South-Eastern Kenya', in A Mynett (ed.), *Deltas of the future and what happens upstream*, 36th IAHR World Congress, La Hague, 28 June - 3 July 2015, IAHR.

de Trincheria, J, Wibbing, J, Leal, W & Otterphohl, R 2016, 'Practical recommendations to prevent, restore and rehabilitate silted-up sand storage dams in arid and semi-arid areas', in RWSN (ed.), *Water for Everyone*, 7th RWSN Forum, Abidjan, Côte d'Ivoire, 29 Nov - 02 Dec 2016, RWSN, viewed 22 November 2016, <https://rwsnforum7.files.wordpress.com/2016/11/full_paper_0201_submitter_0274_detrincheria_josep1.pdf>.

Dillon, P 2005, 'Future management of aquifer recharge', *Hydrogeology Journal*, vol. 13, no. 1, pp. 313–6.

Gale, I & Dillon, P 2005, *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas*, United Nations Educational, Scientific and Cultural Organization, Paris, viewed 30 December 2016.

Goodrich, DC, Kepner, WG, Levick, LR & Wigington, PJ 2018, 'Southwestern Intermittent and Ephemeral Stream Connectivity', *JAWRA Journal of the American Water Resources Association*, vol. 54, no. 2, pp. 400–22.

Gur, E & Spuhler, D 2018, 'Sand Dams and Subsurface Dams', in *The SSWM Toolbox*, seecon international gmbh, Switzerland, viewed 20 December 2018, <https://sswm.info/sswm-university-course/module-4-sustainable-water-supply/further-resources-water-sources-hardware/sand-dams-and-subsurface-dams>.

Hadley, RF 1968, 'Ephemeral streams', in *Geomorphology*, Berlin, Heidelberg.

Hanson, G & Nilsson, A 1986, 'Ground-Water Dams for Rural-Water Supplies in Developing Countries', *Ground Water*, vol. 24, no. 4, pp. 497–506.

Hicks, DM 2004, 'Suspended Load', in A Goudie (ed.), *Encyclopedia of geomorphology*, Routledge, London, pp. 1029–30.

Hicks, DM & Gomez, B 2016, 'Sediment transport', in GM Kondolf & H Piégay (eds), *Tools in fluvial geomorphology*, John Wiley & Sons, Chichester UK, pp. 324–56.

Hussey, SW 2007, *Water from sand rivers: Guidelines for abstraction*, Water, Engineering and Development Centre (WEDC), Loughborough University, United Kingdom.

Imran, J & Parker, G 2008, 'Sediment Transport', in MH Chaudhry (ed.), *Open-channel flow*, 2nd edn, Springer, New York, pp. 453–77.

Jaeger, KL, Sutfin, NA, Tooth, S, Michaelides, K & Singer, M 2017, 'Geomorphology and Sediment Regimes of Intermittent Rivers and Ephemeral Streams', in T Datry, N Bonada & AJ Boulton (eds), *Intermittent rivers and ephemeral streams: Ecology and management*, Academic Press, Elsevier, London, United Kingdom, pp. 21–49.

Julien, PY 2002, *River mechanics*, Cambridge University Press, Cambridge.

Klopfer, DE 2010, 'Grundwasserdämme in semiariden Klimazonen: Eine wasserwirtschaftliche Planungshilfe - Fallbeispiel aus dem äthiopischen Hochland' (German), Diplomarbeit, FH Münster, Münster.

Knoop, L, Sambalino, F & van Steenbergen, F 2012, *Securing water and land in the Tana basin: A resource book for water managers and practitioners*, 3R Water Secretariat, Wageningen.

Lasage, R, Aerts, J, Mutiso, G-C & Vries, A de 2008, 'Potential for community based adaptation to droughts: Sand dams in Kitui, Kenya', *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 33, 1-2, pp. 67–73.

Lasage, R, Aerts, JCJH, Verburg, PH & Sileshi, AS 2015, 'The role of small scale sand dams in securing water supply under climate change in Ethiopia', *Mitigation and Adaptation Strategies for Global Change*, vol. 20, no. 2, pp. 317–39.

Lasage, R & Verburg, PH 2015, 'Evaluation of small scale water harvesting techniques for semi-arid environments', *Journal of Arid Environments*, vol. 118, pp. 48–57.

Liu, X, He, Y, Zhang, T, Zhao, X, Li, Y, Zhang, L, Wei, S, Yun, J & Yue, X 2015, 'The response of infiltration depth, evaporation, and soil water replenishment to rainfall in mobile dunes in the Horqin Sandy Land, Northern China', *Environmental Earth Sciences*, vol. 73, no. 12, pp. 8699–708.

Maddrell, SR 2018, *Sand Dams: A Practical & Technical Manual*, Excellent Development.

Maliva, R & Missimer, T 2012, *Arid Lands Water Evaluation and Management*, Springer Berlin Heidelberg, Berlin, Heidelberg.

Nanoso, GC & Gibling, M 2004, 'Alluvial Channel', in A Goudie (ed.), *Encyclopedia of geomorphology*, Routledge, London, pp. 133–9.

Nissen-Petersen, E 2000, *Water from sand rivers: A manual on site survey, design, construction, and maintenance of seven types of water structures in riverbeds*, RELMA technical handbook series, vol. 23, Regional Land Management Unit (RELMA); Swedish International Development Cooperation Agency (Sida), Nairobi Kenya.

——2006, *Water from dry riverbeds: How dry and sandy riverbeds can be turned into water sources by hand-dug wells, subsurface dams, weirs and sand dams.*, ASAL Consultants Ltd. & Danish International Development Agency, Kenya.

Onder, H & Yilmaz, M 2005, 'Underground dams: A Tool of Sustainable Development and Management of Groundwater Resources', *European Water Resources Association*, vol. 11, no. 12, pp. 35–45, viewed 10 September 2020, <http://www.ewra.net/ew/pdf/EW_2005_11-12_05.pdf>.

Pauw, WP, Mutiso, S, Mutiso, G, Mutiso, HK, Lasage, R & Aerts, J 2008, *An assessment of the social and economic effects of the Kitui sand dams*, IVM Report R-08/08, Instituut voor Milieuvraagstukken, Amsterdam, viewed 20 December 2018, <https://research.vu.nl/ws/portalfiles/portal/2415504/R-08-08.pdf>.

Pereira, LS, Cordery, I & Iacovides, I 2009, *Coping with Water Scarcity*, Springer Netherlands, Dordrecht.

Powell, DM, Reid, I, Laronne, JB & Frostick, L 1996, 'Bed load as a component of sediment yield from a semiarid watershed of the northern Negev', in DE Walling & BW Webb (eds), *Erosion and sediment yield: Global and regional perspectives*, IAHS publication, no. 236, International Symposium, Exeter, UK, 15 - 19 July 1996, University of Exeter, IAHS Press, Wallingford, pp. 389–98.

Quilis, RO, Hoogmoed, M, Ertsen, M, Foppen, JW, Hut, R & Vries, A de 2009, 'Measuring and modeling hydrological processes of sand-storage dams on different spatial scales', *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 34, 4-5, pp. 289–98.

Quinn, R, Avis, O, Decker, M, Parker, A & Cairncross, S 2018, 'An Assessment of the Microbiological Water Quality of Sand Dams in Southeastern Kenya', *Water*, vol. 10, no. 6, p. 708.

Quinn, R, Rushton, K & Parker, A 2019, 'An examination of the hydrological system of a sand dam during the dry season leading to water balances', *Journal of Hydrology X*, vol. 4, p. 100035.

Rainwater Harvesting Implementation Network (RAIN) 2008, *A practical guide to sand dam implementation: Water supply through local structures as adaptation to climate change*, Rainwater Harvesting Implementation Network, Amsterdam, viewed 22 November 2016,

<http://www.samsamwater.com/library/Sand_dam_manual_FINAL.pdf>.

Ryan, C & Elsner, P 2016, 'The potential for sand dams to increase the adaptive capacity of East African drylands to climate change', *Regional Environmental Change*, vol. 16, no. 7, pp. 2087–96.

Seely, M, Henderson, J, Heyns, P & Jacobson, P 2003, 'Ephemeral and endoreic river systems: Relevance and management challenges', in A Turton, PJ Ashton & E Cloete (eds), *Transboundary rivers, sovereignty and development: Hydropolitical drivers in the Okavango River basin*, African Water Issues Research Unit; Green Cross International, Pretoria, South Africa, pp. 187–212.

Teel, WS 2019, 'Catching Rain: Sand Dams and Other Strategies for Developing Locally Resilient Water Supplies in Semiarid Areas of Kenya', in Y Bamutaze, S Kyamanywa, BR Singh, G Nabanoga & R Lal (eds), *Agriculture and Ecosystem Resilience in Sub Saharan Africa: Livelihood Pathways Under Changing Climate*, Climate Change Management, Springer International Publishing, Cham, pp. 327–42.

Thornes, JB 2009, 'Catchment and Channel Hydrology', in AJ Parsons & AD Abrahams (eds), *Geomorphology of desert environments*, 2nd edn, Springer, Dordrecht, pp. 303–32.

Tuinhof, A, Olsthoorn, T, Heederik, JP & de Vries, J 2003, 'Management of aquifer recharge and subsurface storage: A promising option to cope with increasing storage needs', in A Tuinhof & JP Heederik (eds), *Management of aquifer recharge and subsurface storage: Making better use our largest reservoir*, NNC-IAH publication, vol. 4, Netherlands National Committee for the IAH, Utrecht, The Netherlands, pp. 3–18.

Walker, D, Jovanovic, N, Bugan, R, Abiye, T, Du Preez, D, Parkin, G & Gowing, J 2018, 'Alluvial aquifer characterisation and resource assessment of the Molototsi sand river, Limpopo, South Africa', *Journal of Hydrology: Regional Studies*, vol. 19, pp. 177–92.

Wekesa, SS, Stigter, TY, Olang, LO, Oloo, F, Fouchy, K & McClain, ME 2020, 'Water Flow Behavior and Storage Potential of the Semi-Arid Ephemeral River System in the Mara Basin of Kenya', *Frontiers in Environmental Science*, vol. 8, p. 10254.

Wipplinger, O 1958, 'Storage of Water in Sand', *South West Africa [Namibia] Administration Water Affairs Branch, Windhoek, Namibia*.

Yohannes, M, Haile, M, Ghebreyesus, TA, Witten, KH, Getachew, A, Byass, P & Lindsay, SW 2005, 'Can source reduction of mosquito larval habitat reduce malaria transmission in Tigray, Ethiopia?', *Tropical medicine & international health*, vol. 10, no. 12, pp. 1274–85.