Planning, monitoring and evaluation of the performance and cost-efficiency of sand storage dams in arid and semi-arid areas

Advanced technical training course for practitioners
Kitui, Kenya
3rd February 2017

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Acknowledgements and citation

- These training materials are based on innovative practical recommendations for the siting, monitoring and evaluation of sand storage dams which form part of the PhD research on March 2017 of Josep de Trincheria.

- These training materials are also based on know-how and experience of Erik Nissen-Petersen and his extensive work for more than 50 years on rural water supply in arid and semi-arid areas of sub-Saharan Africa with ASAL Consultants Ltd. To his efforts and insightful observations, we all practitioners who have learnt from his work, are most grateful.

- These materials should be cited as it follows:

Goals

• To showcase practical recommendations to tap into naturally available alluvial water in seasonal sandy streams in the most cost-efficient manner.

• To showcase simple but robust monitoring and evaluation methods to select, site and design the most cost-efficient water option in seasonal sandy streams.
This presentation

1. Tapping into the natural alluvial capacity of the riverbed.
2. Structures for enlarging the natural capacity of the riverbed, if necessary.
3. Practical exercise.
If a sandy dry riverbed is able to yield enough water to meet local community needs, either in terms of numbers and/or uses, there is no need to build a subsurface dam or a sand storage dam!

→ Always consider tapping into already available water in the riverbed with upgraded waterholes and different types of shallow wells connected to the reservoir

Why?
How to know if this is the case?
It is possible to tap into this water with little investment

- Low investment and low effort, highest cost-efficiency, simplicity and robustness
- Funds available can be invested on pumping and conveyance systems to make the water available at the household and/or small-scale irrigation, among others!
- **BUT:** Need to be able to identify where this water is, how much there is and if it is enough to meet the needs of the beneficiaries

Nissen-Petersen, 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 storage dams. ASAL Consultants Limited for the Danish International Development Assistance: www.waterforaridland.com

How to systematically do this?

1. Identify a suitable catchment ✔
2. Identify a suitable riverbed ✔
3. Locate underground reservoirs and dykes
4. Evaluate sand storage capacity, water yield, supply and cost-efficiency, water needs of beneficiaries
5. Select the most cost-efficient, simple and robust intervention

Note: We will not discuss steps 1 and 2 have already been implemented by the attendants of the course in cooperation with Kitui’s SEKU University.
Natural storage of shallow groundwater in sandy dry riverbeds

For a riverbed to naturally supply water there must always be situated a natural underground dike which prevent water from seeping downstream through the sand and forms a natural underground reservoir.

This is the reason why in some sections there is water during the dry season, poor rainfall years and droughts, which are usually central water points for local communities.

Where is this water?

Quick and simple yet accurate methods to locate shallow groundwater and underground dykes
How to find suitable sections in the riverbed?

1. Location and types of water indicating trees
2. Location of waterholes and hand-dug wells
3. Location and types of rocks and boulders
4. Coarseness of sand sediments
5. No calcrete
6. Avoid building in bends of the river

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How to locate underground reservoirs and dykes
A combination of 3 quick and simple methods:

1) Waterholes with water during dry periods
2) Natural indicators, especially, water-indicating trees
3) 1-day probing of the width and depth of sand sediments in the riverbed
Waterholes in the riverbed during the dry season

- Waterholes that yield water during the dry season indicate the presence of shallow groundwater.
- The length of time and water used for the beneficiaries give a first indication of the yield capacity of the riverbed.

Natural indicators of shallow GW

1. The most successful natural indicator of good-quality ground water at shallow depth so far identified is *Acacia robusta* (Munina).
   Where this tree is found and supported by topographical indicators, ground water can be obtained at depths of less than 10 m.

2. *Acacia gerrardii* (Muthithiu), *Acacia xanthophloea* (Mulela), and *Fikus sur* (Mukuyu) are all useful indicators of ground water at shallow depth and their presence in conjunction with *A. robusta* (Munina) confirms a good site.

3. Absence of termite mounds.

4. Green cover during the dry season.
## Other water-indicating trees (Phreatophytes)

<table>
<thead>
<tr>
<th>Botanical name</th>
<th>Kiswahili</th>
<th>Kikamba</th>
<th>Depth to water</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Cyperus rotundus</em></td>
<td>Kiindiu</td>
<td>3 m to 7 m</td>
<td></td>
</tr>
<tr>
<td><em>Vangueria tomentosa</em></td>
<td>Kikomoa</td>
<td>5 m to 10 m</td>
<td></td>
</tr>
<tr>
<td><em>Grewia spp</em></td>
<td>Itiliku</td>
<td>7 m to 10 m</td>
<td></td>
</tr>
<tr>
<td><em>Markhamia lutea</em></td>
<td>Chyoo</td>
<td>8 m to 15 m</td>
<td></td>
</tr>
<tr>
<td><em>Hyphaene compressa</em></td>
<td>Ilala</td>
<td>9 m to 15 m</td>
<td></td>
</tr>
<tr>
<td><em>Borassus aethiopum</em></td>
<td>Kyatha</td>
<td>9 m to 15 m</td>
<td></td>
</tr>
<tr>
<td><em>Ficus vasta</em></td>
<td>Mumbu</td>
<td>9 m to 15 m</td>
<td></td>
</tr>
<tr>
<td><em>Ficus natalensis</em></td>
<td>Muumo</td>
<td>9 m to 15 m</td>
<td></td>
</tr>
<tr>
<td><em>Ficus sycomorus</em></td>
<td>Mukuyu</td>
<td>9 m to 15 m</td>
<td></td>
</tr>
<tr>
<td><em>Kigelia Africana</em></td>
<td>Muatini</td>
<td>9 m to 20 m</td>
<td></td>
</tr>
<tr>
<td><em>Newtonia hildebranditi</em></td>
<td>Mukami</td>
<td>9 m to 20 m</td>
<td></td>
</tr>
<tr>
<td><em>Acacia elatior</em></td>
<td>Munina</td>
<td>9 m to 20 m</td>
<td></td>
</tr>
</tbody>
</table>

Geophysical survey at the site level

1-day field survey to measure depth and width of sand sediments of the specific section (500m-1,000 m) of the riverbed where the groundwater dam is to be built →

1. To tap into the natural capacity of the riverbed in a cost-efficient manner:
   ▪ The spillway should be built at the shallowest point where there is an underground dyke.
   ▪ The maximum depth of sand should be located downstream of the spillway.

2. To disregard specific sites with low potential before the implementation takes place (seepage, evaporation, siltation)

→ Optimise performance, cost-efficiency and benefit to local communities

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Probing

• The most simple method to survey the riverbed is to hammer iron rods of 2-4 m (14-16 mm) into the ground
• Along 500 m – 1,000 m
• Sub-sections of intervals of 20 or 10 m
• Measurement of the depth of sand and water at least once in the middle of the sub-section
• Need to measure other variables

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Other variables to record

1. Gradient of the riverbed
2. Texture of sand
3. Floor under the sand
4. Height of the riverbanks
5. Items seen on the banks

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Specific yield of sand

The specific yield is given by:

\[ n = \frac{Y_S}{V_S} \]

where \( Y_S \) is the volume of drained water (L) and \( V_S \) is the volume of sand (L)

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Longitudinal profile and plan
Hydrological evaluation of the reservoir

- To evaluate if the water yield of the sand reservoir can meet the water needs of the beneficiaries
- To identify the most cost-efficient option to implement
  - Waterholes and/or hand-dug wells
  - Pumping and conveyance systems
  - Subsurface dams
  - Sand storage dams

Simple and quick method to estimate sand storage capacity and water yield

The extractable volume of water from a sand dam is estimated using the formula below multiplied by the extraction percentage

\[ Q = \frac{L \times T \times D}{6} \]

where \( Q \) is the capacity in cubic metres, \( L \) is the length of the dam wall in metres at full supply level, \( D \) is the maximum depth in metres, and \( T \) is the throwback in metres.

This assumes that the basin is a pyramid whose base is the dam wall.

For example:

25% of water can be extracted from 5,000 m\(^3\) sand = 1,250 m\(^3\) water

5% of water can be extracted from 5,000 m\(^3\) sand = 250 m\(^3\) water
A more accurate method to estimate sand storage capacity and water yield
Sand storage capacity of each section

• General equation to estimate the capacity of a water reservoir:

\[ C_P = K \times D \times W \times T \]

where \( C_P \) is the reservoir capacity (m\(^3\)), \( K \) is a constant to reflect the geometrical shape of a reservoir, \( D \) and \( W \) are the depth and width of each section (m), respectively, and \( T \) is the length of the probing section (m).


Evaporation losses

• To take into account evaporation losses, an evaporation depth of 0.6 m (Hellwig, 1973) – 1.0 m (Wipplinger, 1958) should be taken into account. This means:

  • $D_E = D - [0.6-1.0] \text{ (m)}$
  • $C_{PE} = K \times D_E \times W \times T \text{ (m}^3\text{)}$

Geometrical shape

Total sand storage capacity

\[ C_T = \sum_{1\,\text{to}\,n} C_i \]

\[ C_T = C_{P1} + C_{P2} + C_{P3} + \ldots + C_{Pn} \]

- where \( C_T \) is the total reservoir capacity (\( m^3 \)), \( C_P \) is the reservoir capacity of each probing point


LEVELLING A RIVERBED

Water yield of a sand dam

\( Y_A \) indicates the capacity of the reservoirs to yield water per year taking into account the volume of sand accumulated and the associated specific yield of the sand sediments. The formula is given by

\[
Y_A = C_T \times n \times R
\]

- where \( Y_A \) is the annual water yield of the sand reservoir (m\(^3\)/year) and \( R \) is a constant which reflects the number of rainy seasons in the study area.


Seepage losses

To take into account seepage losses, the formula is given by

- \( Y_S = Y \times Sp \)
  - where \( Y_E \) is the yield after accounting seepage (m\(^3\)) and \( Sp \) is a conservative constant which aims to reflect minimum potential seepage losses (%).

- \( Sp = 10\% \) (Stephens, 2010)


Water supply capacity

• \( S_S = Y_D / C_{oD} \)
  
  □ where \( S_S \) is the total number of households supplied by the groundwater dam during one dry season (households), \( Y_D \) is the effective water yield of the sand dam during that specific dry season (m\(^3\)) and \( C_{oD} \) the water needs per household during that specific dry season (m\(^3\)).

• \( C_{oD} \) is given by \( C_{oD} = C_{oH} \times L_D \)
  
  □ where \( C_{oH} \) is the total consumption of one household per day (m\(^3\)/day) and \( L_D \) is the length of the dry season (days).


Annualised construction costs

- \[ AC_{\text{sand dam}} = CC_{\text{sand dam}} \times i \times \frac{(1+i)^n}{(1+i)^n - 1} + AOM_{\text{sand dam}} \]  

- where \( AC \) are the annualised costs (USD/year), \( CC \) are the capital costs of the sand dam (USD), \( i \) is the interest rate (%), \( n \) is the lifespan of the sand dam (years), and \( AOM \) are the annual operation and maintenance costs (USD).

- \( AOM = 0 \)
- \( i = 5\% \) (Jafaar, 2014).
- \( N = 20 \) years (Batchelor et al., 2011).


Cost-efficiency

- CE = \frac{CC \text{ sand dam (EUR)}}{\text{Water Yield (m}^3\text{) or Water Supply (households)}}

- ACE = \frac{AC \text{ sand dam (EUR/year)}}{\text{Water Yield (m}^3\text{) or Water Supply (households)}}

where CE is the capital cost-efficiency of the annual water yield (EUR/m$^3$) or supply capacity (EUR/household), and ACE is the annualised cost-efficiency of the annual water yield (EUR/m$^3\cdot$year) or supply capacity (EUR/household·year).


The probing and evaluation can be carried out during and after the construction so as to monitor and evaluate the performance and cost-efficiency.

The second method is recommended to be used for the monitoring and evaluation exercise.

Selecting the most cost-efficient, simple and robust intervention on the riverbed

→ Structures for tapping into the natural water yield capacity of dry riverbeds
Upgraded waterholes and hand-dug wells

- More attention should be given to low-cost water projects incorporating upgraded waterholes, hand-dug wells and sub-surface dams.

- The investment can be used to upgrade waterholes and hand-dug wells → A pump, a water reservoir and a water kiosk.

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Structures for enlarging the water yield capacity of dry riverbeds: Subsurface dams and sand storage dams
Key Remark!

1. A subsurface dam should always be considered before than a sand storage dam because of higher cost-efficiency, simplicity and robustness to erosion and siltation.

2. Only if the water yielded for a subsurface dam is not enough to meet the needs of the beneficiaries, a sand storage dam is the most cost-efficient option.
Subsurface dams
Practical recommendations: Subsurface dams

Source: Vétérinaires sans Frontières (2006)
Practical recommendations: Subsurface dams
Practical recommendations: Subsurface dams
Practical advantages of subsurface dams

- Subsurface dams show inherent higher cost-efficiency and strategic advantages as compared to sand storage dams, provided the water yielded is enough to meet local communities:

1) No siltation
2) No vulnerability to the erosion of floods: no wing walls, lower erosive forces, lower hydraulic pressure
3) Higher lifespan
4) No maintenance or repairs required.
5) Lower capital investment because it will always require lower volumes of materials and can be built of clayey soil
6) Natural deposited sand sediments produce reservoirs with higher specific yields (good levels of sorting and texture)
7) They can always be built in 1-stage, i.e. faster and easier
8) SDs can be implemented in low riverbanks because there is no need to build wing walls

Practical recommendations: Subsurface dams

- (-) SSDs must be implemented where there are reservoirs with deep layers of sand

- (-) SSDs have a lower impact on the reduction of flood intensity and erosion → they do not reduce the gradient of the original riverbed

- (-) SSDs cannot be built at the head of the valley → SDs will have lower performance and cost-efficiency
Free storage capacity and lower costs by building on underground dykes

The longitudinal profile shows the underground dyke that traps water for the deepest point.

If a subsurface dam is built onto the dyke, it will raise the water to near the surface of the riverbed, thereby increasing the volume of water for the well.

Minimum construction costs as the dyke provides a free part of the dam wall and de-watering is not required as water cannot stand on a dyke.

### Construction costs of a subsurface dam

<table>
<thead>
<tr>
<th>Size of subsurface dam</th>
<th>Construction material</th>
<th>Ksh</th>
<th>US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 m long x 2.1 m high</td>
<td>Soil from a nearby riverbank</td>
<td>156,400</td>
<td>1,777</td>
</tr>
<tr>
<td>24 m long x 2.1 m high</td>
<td>Reinforced rubble stone masonry</td>
<td>771,075</td>
<td>8,762</td>
</tr>
<tr>
<td>24 m long x 2.1 m high</td>
<td>Reinforced concrete in timber shuttering</td>
<td>1,857,250</td>
<td>21,105</td>
</tr>
<tr>
<td>24 m long x 2.1 m high</td>
<td>Dam-liner (Geo-membrane)</td>
<td>192,510</td>
<td>2,188</td>
</tr>
</tbody>
</table>

Construction costs include survey, design, permits, construction materials and labour + 15% overhead.

The dam wall should be built from the most clayey soil available near the site to reduce transport costs.

The most clayey soil is determined by filling soil samples into bottomless plastic containers and saturating them with water.

The soil sample having the slowest infiltration rate is the most clayey soil that can prevent water in the dam reservoir from seeping through the dam wall.

STANDARD DESIGN OF A SUBSURFACE DAM BUILT OF SOIL

Plan of a subsurface dam seen from above

Longitudinal profile of the dam wall

Cross section of the dam wall. Note that the crest should be 0.6 m-1.0 m below the surface of the riverbed

Practical exercise
1. Identify the best depression to sink a hand-dug well
2. Identify the best dyke to build a subsurface and a sand storage dam
<table>
<thead>
<tr>
<th>Throwback</th>
<th>500 Yield</th>
<th>667</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Natural depth</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Specific Yield</td>
<td>20%</td>
<td></td>
</tr>
</tbody>
</table>

30 households | 30 Needs | 540 |
5 j/d | 100 |
6 months | 180 |

<table>
<thead>
<tr>
<th>Throwback</th>
<th>500 Yield</th>
<th>667</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Natural depth</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Specific Yield</td>
<td>20%</td>
<td></td>
</tr>
</tbody>
</table>

30 households | 30 Needs | 1080 |
10 j/d | 200 |
6 months | 180 |

<table>
<thead>
<tr>
<th>Throwback</th>
<th>500 Yield</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Depth with a SD 2 m</td>
<td>6,00</td>
<td></td>
</tr>
<tr>
<td>Specific Yield</td>
<td>20%</td>
<td></td>
</tr>
</tbody>
</table>

30 households | 50 Needs | 1800 |
10 j/d | 200 |
6 months | 180 |

Identifying the most cost-efficient structure to meet the needs of the local communities

Storage capacity

1. An approximate estimate of the capacity is

\[ Q = \frac{L \times T \times D}{6} \]

where \( Q \) is the capacity in cubic metres, 
\( L \) is the length of the dam wall in metres at full supply level, 
\( T \) is the throwback in metres, and 
\( D \) is the maximum depth in metres, and

This assumes that the basin is a pyramid whose base is the dam wall.
Further cooperation and research

We encourage implementing agencies to **contact us to scale up this research!**

→ Large-scale PME, restoring and rehabilitation programme on silted-up SDs.

Please, **send an email to:**
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Thank you for your attention!
References

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